

Delineation of Groundwater Region 65: Zululand Coastal Plain Aquifer, KwaZulu- Natal

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Abstract

The Zululand Coastal Aquifer or Groundwater Region 65 is the largest primary porosity aquifer in South Africa. Despite the veneer of well rounded, medium size sand grains, the subsurface environment comprises geological units with unique hydrogeological properties.

Utilising Vegter's (2001) methodology, nine laterally delineated groundwater regions (Q and Qb; Qm; Qpd; Kz, Pv and Pvo; JI and Zn; Nhl, Nng and ZB; Tu and Ntu) were identified however, data was a major shortcoming. Therefore to gain clarity, the hydrostratigraphic units were then vertically delineated using geological data derived from borehole logs and chronologically aligned with the regional geology to produce four hydrostratigraphic units.

Surficial sands of the Sibayi Formation constitute hydrostratigraphic unit 1 which has the highest permeability, porosity and hydraulic conductivity (vertical and horizontal). The shallow to unconfined groundwater table facilitates abstraction (yield of <0.4 L/s) in the rural communities. However, it was recently reported that the cover sands are capable of generating higher yields (10 L/s to >25 L/s).

Hydrostratigraphic unit 2 (Kwabonambi Formation) and 3 (Kosi Bay and Port Dunford Formations) are considered aquitards on account of incessant vertical leakage. Hydrostratigraphic unit 2 represents the most prominent perched aquifer in the study area while hydrostratigraphic unit 3 is illustrated by several expansive wetlands.

Hydrostratigraphic unit 4 (Uloa Formation) is a leaky, semi-confined to confined aquifer. It is often utilised for production purposes on account of high borehole yields (6.7 to 28 L/s) which are a function of lithology thickness and karstification.

The impermeable Zululand Group represents the hydrogeological basement for the aforementioned hydrostratigraphic units. Marked by reduced hydrogeological properties, low borehole yields (<0.1 L/s) and highly saline water, the Zululand Group is unfeasible to exploit as a potable resource.

The discussions above attest to the presence of a shallow (hydrostratigraphic unit 1, 2 and 3) and deep aquifer (hydrostratigraphic unit 4). Hydrostratigraphic unit 1 and 2 are extensive while the remaining hydrostratigraphic units are limited and erratically distributed across the study area. Therefore, boreholes are unlikely to intercept all four hydrostratigraphic units including the hydrogeological basement in a vertically, sequential manner.

The degree of surface water – groundwater interaction was quantified using the Herold's Curve Fitting and the Saturated Volume Fluctuation Methods. The results confirmed that groundwater sustains major lakes and smaller streams and that there is constant interaction between the shallow aquifer and the surrounding surface water bodies.

Anthropogenic activities were delineated on the basis of land use. Forestry and commercial sugar cane farming were the dominant anthropogenic activities occurring on a regional scale while mining, urban and or industrial land use, rural practises and salt water intrusion were localised. On account of its hydrogeological properties and shallow to unconfined groundwater table, the Zululand Coastal Aquifer is extremely vulnerable to pollution.

Keywords

Groundwater Region 65

Zululand Coastal Aquifer

Primary porosity

Quaternary Age deposits

Maputaland

Shallow groundwater

Surface water – groundwater interaction

Groundwater contribution to surface water bodies

Anthropogenic impacts to primary aquifers

Declaration

I, Sathisha Barath, declare that the dissertation “**Delineation of Groundwater Region 65: Zululand Coastal Aquifer, KwaZulu-Natal**” submitted in fulfilment for the degree Magister Scientiae in Environmental Sciences (specialising in Hydrology and Geohydrology) is my own work, that it has not been submitted before for any degree or examination in any other university and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

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Date: 01 October 2015

Preface and Acknowledgments

To the Supreme Lord, Shree Krishna, thank you for blessing me with the courage, opportunity and ability to compile this dissertation.

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List of Abbreviations

Acronym	Definition
AFYM	Aquifer Firm Yield Model
<i>c</i>	Approximately
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
ET	Evapotranspiration
ETM	Enhanced Thematic Mapper
GRA	Groundwater Resource Assessment
GRIP	Groundwater Resource Information Project
K	Hydraulic conductivity
KZN	KwaZulu-Natal
mamsl	meters above mean sea level
Ma	Million years
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
mbgl	meters below ground level
NGA	National Groundwater Archive
RBM	Richards Bay Minerals
SVF	Saturated Volume Fluctuation
SMOW	Standard Mean Ocean Water
T	Transmissivity
TDS	Total Dissolved Solids
TM	Thematic Mapper
WARMS	Water Authorisations Resource Management System
WRC	Water Research Commission
WMA	Water Management Area
ZCA	Zululand Coastal Aquifer
ZCP	Zululand Coastal Plain

Table of Contents

Abstract.....	ii
Keywords	iv
Declaration.....	v
Preface and Acknowledgments	vi
List of Abbreviations.....	vii
Table of Contents.....	viii
1 Introduction and Background	1
1.1 Preamble	1
1.2 Objectives	2
2 Literature Review.....	4
2.1 Geology	4
2.2 Hydrogeology.....	7
2.3 Surface Water – Groundwater Interaction	13
2.4 Anthropogenic Impacts	15
3 Physiographic Description of the Zululand Coastal Plain	19
3.1 Location	19
3.2 Topography.....	21
3.3 Climate.....	23
3.4 Oceanography	23
3.5 Vegetation.....	25
3.6 Hydrology.....	27
3.7 Geology	30
3.7.1 Pre-Cretaceous Geology	30
3.7.2 Lebombo Group.....	30
3.7.3 Zululand Group.....	31
3.7.4 Maputaland Group.....	32
4 Methodology and Approach	39
4.1 Methodology Adopted for the Dissertation.....	39
4.2 Vegter’s (2001) Methodology	40
4.3 Delineation of Hydrostratigraphic Units using Geology.....	41
4.4 Methodology for the Delineation of Anthropogenic Activities	42
4.5 Assumptions and Limitations.....	43
5 Regional Hydrogeological Characteristics of the Zululand Coastal Aquifers	45
5.1 Regional Hydrogeology and Groundwater Occurrence	45
5.2 Recharge	53
5.3 Groundwater Levels	55

5.4	Groundwater Hydraulics.....	56
6	Delineation of the Groundwater Region 65 – Zululand Coastal Aquifer.....	59
6.1	Introduction	59
6.1.1	Simplified Geology.....	59
6.1.2	Borehole Distribution	61
6.1.3	Water Level Analysis	62
6.1.4	Borehole Depths.....	73
6.1.5	Borehole Yields	74
6.1.6	Water Strikes.....	75
6.1.7	Aquifer Parameters.....	81
6.1.8	Geochemistry	82
6.2	Delineation of Hydrostratigraphic Units	84
6.2.1	Hydrostratigraphic Unit 1	88
6.2.2	Hydrostratigraphic Unit 2	88
6.2.3	Hydrostratigraphic Unit 3	89
6.2.4	Hydrostratigraphic Unit 4	89
6.2.5	Hydrogeological Basement of the ZCP	90
6.3	Hydrogeological Characteristics for the Vertically Delineated Hydrostratigraphic Units ...	92
6.3.1	Shallow Aquifers.....	92
6.3.2	Deep Aquifers.....	99
6.4	Surface Water – Groundwater Interaction	104
6.4.1	Quantification of Surface Water – Groundwater Interaction	105
6.4.2	Interaction of Rivers with Groundwater	113
6.4.3	Wetland Distribution.....	114
6.4.4	Interaction between Lakes and Groundwater.....	114
7	Anthropogenic Impacts	119
7.1	Delineation of Anthropogenic Impacts.....	123
7.2	Types of Anthropogenic Activities and its Associated Impacts	125
7.2.1	Forestry	126
7.2.2	Agriculture	129
7.2.3	Mining.....	132
7.2.4	Urban and Industrial Land Use	136
7.2.5	Rural practises.....	139
7.2.6	Salt water intrusion	142
8	Conclusions and Recommendations.....	144
	Reference List.....	147
	Appendices	156
	Appendix A: MAP Graphs for Several Quaternary Catchments in the ZCP.....	157

Appendix B: Flow data from the DWA Gauges in the Study Area 162

List of Tables

Table 3-1: Stratigraphic Column for the Maputaland Group (referenced from both Watkeys <i>et al.</i> , (1993) and Meyer <i>et al.</i> , (2001)).....	33
Table 3-2: Categorisation of Geological Formations Recorded in Borehole Logs.....	38
Table 5-1: Borehole Distribution per Quaternary Catchment.....	47
Table 5-2: Registered Groundwater Usage on the WARMS Database for the Umkhanyakhude District Municipality	49
Table 5-3: Aquifer Characteristics for the Quaternary Catchments in the Zululand Coastal Plain – GRA I Database, (DWAF, 1995 – 2003).	51
Table 5-4: Hydrogeological Properties of the Quaternary Catchments in the Zululand Coastal Plain – GRA II Database, (DWAF, 2003 - 2005).	51
Table 5-5: Hydrogeological Properties of the Quaternary Catchments in the Zululand Coastal Plain under Normal and Dry or Drought Conditions - GRA II Database, (DWAF, 2003 – 2005).	52
Table 5-6: Mean Annual Precipitation (MAP) and Mean Annual Runoff (MAR) for the Quaternary Catchments in the ZCP (mm/a), (GRIP Database; WRC, 2005).....	54
Table 5-7: Recharge for the Zululand Coastal Aquifer as a Percentage of MAP (cited from literature).	55
Table 6-1: Simplified Geology	59
Table 6-2: Borehole Distribution in the Simplified Geological Formations (NGA and GRIP Database).	61
Table 6-3: Summary of Average Borehole Depths and Elevations	73
Table 6-4: Summary of Average Borehole Yield and Discharge (L/s).....	74
Table 6-5: Input Parameters and Results for the Aquifer Firm Yield Model	82
Table 6-6: Lateral Delineation of Hydrostratigraphic Units based on Geology	85
Table 6-7: Delineation of Lateral Sub-regions Based on Geological Statistics.....	87
Table 6-8: Vertical Delineation of Hydrostratigraphic Units.....	88
Table 6-9: Aquifer Parameters Cited for Hydrostratigraphic unit 1.....	94
Table 6-10: Aquifer Parameters Cited for Hydrostratigraphic unit 2.....	96
Table 6-11: Aquifer Parameters Cited for Hydrostratigraphic unit 3.....	98
Table 6-12: Aquifer Parameters Cited for Hydrostratigraphic unit 4.....	100
Table 6-13: Partial Groundwater Hydrochemical Data for the Hydrogeological Basement (Zululand Group) in the ZCP (mg/L unless stated otherwise), (GRIP Dataset unless stated otherwise).	103
Table 6-14: Groundwater Contribution to Surface Water.....	106
Table 6-15: Average Monthly Groundwater Contribution to Lakes in the ZCP using the Saturated Flow Volume Method.	110
Table 7-1: Main Sources of Groundwater Pollution with Some of Their Main Characteristics, (Sililo <i>et al.</i> , 2001).....	122
Table 7-2: Dominant Land Use per Quaternary Catchment and Associated Anthropogenic Activity.....	123
Table 7-3: Area under Forestation per Quaternary Catchment, (WRC, 2005).	127

Table 7-4: Water Quality Data from Lake Sibaya at Banda-Banda, (DWAF, 2002).	137
Table 7-5: Common Source of Groundwater Pollution from Industry, BGS (2008) and modified after Morris <i>et al.</i> , (2003).	138

List of Figures

Figure 3-1: Aerial Photograph Showing the Location and Aerial Extent of the Study Area.	20
Figure 3-2: Photograph Showing the Densely Vegetated North-South Orientated Parabolic Dune Cordons.	21
Figure 3-3: Digital Surface Elevation Model for Maputaland, (modified after Smith, 2001).	22
Figure 3-4: Average Sea-surface Temperature (°C) for Southern Africa where the Highest Temperatures are recorded along the East Coast of Africa, (modified after UKDM, 2012).	24
Figure 3-5: Ecological Zones of Maputaland, (modified after Smith, 2001).	26
Figure 3-6: Surface Water Resources in the ZCP and Surrounds, (modified after UKDM, 2012). .	27
Figure 3-7: Quaternary Catchments in the Zululand Coastal Plain.	28
Figure 3-8: Regional Geological Map for the Zululand Coastal Plain, (Watkeys <i>et. al</i> 1993).	32
Figure 3-9: Schematic Representation of the Maputaland Group Lithostratigraphic Units Showing the Relationship between the Formations and Specific Sedimentary Unit. LIG is defined as the Last Interglacial Period, (Porat and Botha, 2008).	34
Figure 5-1: Regional Hydrogeological Map for the ZCP, (DWAF, 1998).	46
Figure 5-2: Distribution of the Borehole Records In the Eight Quaternary Catchments (W12F, W12J, W13B, W23C, W23D, W32B, W32H, and W70A).	48
Figure 5-3: Mean Annual Precipitation Graph for Rainfall Gauges Distributed across the ZCP, (http://www.dwa.gov.za/hydrology).	54
Figure 5-4: Surface Elevation vs Groundwater Elevation for Boreholes Recorded on the GRIP Database.	57
Figure 5-5: Surface Elevation vs Groundwater Elevation for Wells Recorded on the GRIP Database.	57
Figure 5-6: Bayesian Interpolation Map Showing the Groundwater Level (mamsl) for the Zululand Coastal Plain, (GRIP and NGA Database and Water Levels Derived from the Private Sector Reports).	58
Figure 6-1: Simplified Geological Map for Quaternary Catchments W70A, W32B, W32H, W23D, W23C, W12J, W12F and W13B.	60
Figure 6-2: Q – Quaternary Age Deposits, Groundwater Level vs Rank.	62
Figure 6-3: Q – Quaternary Age Deposits, Groundwater Level vs Surface Elevation	62
Figure 6-4: Q – Quaternary Age Deposits, Groundwater Level Distribution.	63
Figure 6-5: Qb – Bluff Formation, Groundwater Level vs Rank	63
Figure 6-6: Qb – Bluff Formation, Groundwater Level vs Topography.	64
Figure 6-7: Qb – Bluff Formation, Distribution of Groundwater Levels.	64
Figure 6-8: Qm – Masotcheni Formation, Groundwater Level vs Rank	65
Figure 6-9: Qm – Masotcheni Formation, Groundwater Level vs Topography	65

Figure 6-10: Qm – Masotcheni Formation, Groundwater Level Distribution.....	65
Figure 6-11: Qs – Salnova Formation, Groundwater Level vs Rank.....	66
Figure 6-12: Qs – Salnova Formation, Groundwater Elevation vs Topography	66
Figure 6-13: Qs – Salnova Formation, Groundwater Level Distribution.....	67
Figure 6-14: Kz - Zululand Group, Groundwater Level Frequency per Depth	67
Figure 6-15: Ntu – Tuma Formation, Groundwater Level vs Rank.....	68
Figure 6-16: Ntu – Tuma Formation, Groundwater Level vs Topography.....	68
Figure 6-17: Ntu, Tuma Formation, Groundwater Level Distribution.....	69
Figure 6-18: Pv - Vryheid Formation, Groundwater Level vs Rank.....	69
Figure 6-19: Pv, Vryheid Formation, Groundwater Level vs Topography	70
Figure 6-20: Pv, Vryheid Formation Groundwater Level Distribution.....	70
Figure 6-21: Pvo, Volksrust Formation, Groundwater Level vs Rank.....	71
Figure 6-22: Pvo, Volksrust Formation, Groundwater Levels vs Topography	71
Figure 6-23: Zn - Nondweni Group, Groundwater Level vs Rank.....	72
Figure 6-24: Zn – Nondweni Group, Groundwater Level vs Topography.....	72
Figure 6-25: Zn – Nondweni Group, Groundwater Level Distribution.....	73
Figure 6-26: Average Borehole Depth and Elevation	74
Figure 6-27: Average Borehole Yield and Discharge (L/s).....	75
Figure 6-28: Average Water Strike Depth (mbgl) and Yield (L/s).....	76
Figure 6-29: Q – Quaternary Deposits Strike Frequency.....	77
Figure 6-30: Qb – Quaternary Deposits Strike Frequency.....	77
Figure 6-31: Qm Strike Frequency	78
Figure 6-32: Qs Strike Frequency	78
Figure 6-33: Kz - Zululand Group Strike Frequency	79
Figure 6-34: Ntu – Tuma Formation Strike Frequency	79
Figure 6-35: Pv – Vryheid Formation Strike Analysis	80
Figure 6-36: Pvo – Volksrust Formation Strike Frequency.....	80
Figure 6-37: Zn – Nondweni Group Strike Frequency	81
Figure 6-38: Piper Diagram for Lithostratigraphic Unit Q, Qs, Qm and Qb.....	83
Figure 6-39: Expanded Durov Plot for Lithostratigraphic Unit Q, Qs, Qm and Qb.....	84
Figure 6-40: Lateral Delineation of Hydrostratigraphic Units Based on Geology.....	86
Figure 6-41: Conceptual Geological Cross-section of the Eastern Shores of Lake St. Lucia which is Modified to show the Vertically Delineated Hydrostratigraphic Units When Present, (modified after Davies <i>et al.</i> , 1992).	91
Figure 6-42: Utilisation of the Shallow Aquifer (Hydrostratigraphic unit 1).	93
Figure 6-43: A Perched Pan used for Domestic Purposes, (Kelbe and Germishuyse, 2010).....	97
Figure 6-44: Schematic Diagram Displaying the Interaction between the Port Dunford and Uloa Formation, (Kelbe and Germishuyse, 2010).....	101
Figure 6-45: Conceptualisation of the Interaction between a Primary Aquifer and a Surface Water Body, (Kelbe and Germishuyse, 2010).....	104

Figure 6-46: Groundwater Seepage along the Shoreline of Lake St. Lucia, (Kelbe and Germishuys, 2010).....	117
Figure 7-1: Pollutant Transport Model, (Schmoll <i>et al.</i> , 2006).....	120
Figure 7-2: Geohydrology Sensitivity Map, (UKDM, 2012).	121
Figure 7-3: Land Use Map for the ZCP and Surrounds, (Ezemvelo, 2011).....	124
Figure 7-4: Distribution of Forestry across the Nine Laterally Delineated Hydrostratigraphic Units	126
Figure 7-5: Plantations in Northeastern KwaZulu-Natal, (modified after Karumbidza, 2006).	127
Figure 7-6: Impact of Forestry on Wetlands, (modified after, Kelbe and Germishuys, 2010).	129
Figure 7-7: Photographs of the Siyaya Lagoon, (modified after, Kelbe and Germishuys, 2010).	132
Figure 7-8: Mining in the Vicinity of Lake Nhlabane, (Google Earth, 2014 (image (a) and (b)) and 2013 (image (c)).....	134
Figure 7-9: Distribution of Informal Settlements across the Nine Laterally Delineated Hydrostratigraphic Units.....	141

1 Introduction and Background

1.1 Preamble

The Zululand Coastal Plain (ZCP) is situated along the northeastern coastline of KwaZulu-Natal (KZN) and encloses the largest primary aquifer in South Africa. The primary aquifer spans across an area of 6,000 km² and comprises unconsolidated Cenozoic aged deposits which are the product of multiple episodes of sea level fluctuations, (Meyer *et al.*, 2001).

Abundance of both surface and groundwater resources including a multitude of groundwater dependant ecosystems has prompted research on understanding the dynamics of the groundwater regime in the ZCP. Using geology, Vegter (2001) delineated a total of sixty-five groundwater regions in South Africa of which the northern ZCP is referred to as Groundwater Region 65.

The subsurface environment of the ZCP comprises several geological formations with unique hydrogeological attributes. This necessitates the delineation of hydrostratigraphic units on the basis of similar geological characteristics in order to quantify the hydrogeological properties of the various hydrostratigraphic units.

Several studies (Worthington (1978); King (1997); Meyer *et al.*, 2001; Schapers (2011) and Jefferes and Green (2012)) have confirmed that a dual aquifer system comprising the shallow and deep aquifer occurs in the ZCP. The laterally extensive shallow aquifer consists of medium grained sand of the Sibaya and Kwambonambi Formation which are commonly referred to as the 'cover sands', (Maud, 1980). The aquifer is intercepted between 1 to 6 meters below ground level (mbgl) and is underlain by the clayey Kosi Bay and Port Dunford Formation, (Worthington, 1978).

According to Vegter (2001), borehole yields in the unconsolidated coastal deposits are highly variable and are a function of the grain size and thickness of the deposit. This was particularly evident as DWAF (2004) reported that the shallow aquifer was extensively utilised for domestic water supply by rural communities across the ZCP. Groundwater abstraction was via a series of shallow unlined wells, shallow concrete ring supported open wells and recently, shallow tube wells which were equipped with hand pumps on account of their low yields (average yield of 0.4 L/s, GRIP database). However, studies undertaken by Jeffares and Green (2012), indicate that the cover sands are very productive aquifers which can yield >25 L/s when wide diameter boreholes are installed into coarse to medium grain size sands.

Rainfall is the principal recharge mechanism, (Kelbe and Germishuys, 2001) and the highly permeable nature of the sands promotes rapid recharge to the intergranular aquifer,

(WRC, 2011). However, recharge via seepage from several pans, lakes and shallow peat swamps supplements the aquifer, (Parsons, 2004).

The karst weathered shelly coquina and calcarenite of the Uloa Formation (Meyer *et al.*, 2001) is generally intercepted between 30 to 45 mbgl. The erratically distributed aquifer generates borehole yields ranging from 0.45 to 30 L/s. Due to high transmissivity and storativity properties, the deeper aquifer is commonly used for production purposes, (DWAF, 2004).

The primary aquifer is linked to several major lakes and associated wetlands, (Kelbe and Germishuys, 2010). Several authors (Worthington, 1978; Meyer *et al.*, 2001; Kelbe and Germishuys (2010)) have concluded that this delicate balance is often disrupted by anthropogenic activities in the ZCP.

Land use in the ZCP is dominated by commercial forestry and agriculture however activities such as mining and those related to urban, rural and industrial land use also induce environmental pressures. On account of its hydrogeological properties, the primary aquifer is considered most susceptible to pollution. Therefore, anthropogenic impacts associated with the land use or activities mentioned above frequently have profound impacts on the aquifer and its associated environments.

1.2 Objectives

Various investigations have been undertaken on the Zululand Coastal Aquifer (ZCA). Therefore all pertinent data will be collated into a single reference which will provide concise information on the various aquifer types and associated hydrogeological characteristics.

The objectives for the study are summarised below.

- Consolidate pertinent data for the study in a concise and accurate manner.
- Provide a detailed physiographic and geological description of the study area.
- Delineate hydrostratigraphic units using Vegter's (2001) methodology and geology.
- Discuss aquifer characteristics for the delineated hydrostratigraphic units.
- Quantify the level of surface water – groundwater interaction and examine the relationship between the groundwater and surface water bodies.
- Delineate anthropogenic activities and discuss its associated impacts on the underlying aquifer.

The dissertation is divided into eight chapters of which **Chapter 1** provides a background into the Zululand Coastal Aquifer including a brief description of the respective aquifer's hydrogeological properties and vulnerability to pollution. The objective of the dissertation is

also established in this chapter. A literature review of pertinent research undertaken in the study area is discussed in **Chapter 2**. Discussions pertaining to the physical location, topography, climate, oceanography, vegetation, hydrology and a comprehensive description of the geology of the ZCP are presented in **Chapter 3**. The methodology and approach adopted for the study is detailed in **Chapter 4**. Regional hydrogeological characteristics of the ZCA are presented in **Chapter 5**. Delineation of Groundwater Region 65 based on the geology, a discussion of the hydrogeological properties for the delineated hydrostratigraphic units and the examination of the surface and groundwater relationships are discussed in **Chapter 6**. Delineation of anthropogenic impacts in the study area and subsequent discussions of these impacts on the subsurface environment and aquifer is examined in **Chapter 7**. Conclusions and recommendations emanating from this dissertation are summarised in **Chapter 8** followed by a list of literature sources which are presented at the end of this dissertation.

2 Literature Review

Numerous studies have been undertaken in the ZCP however these investigations were strategically located and largely focused around the Richards Bay area. Therefore, data relating to this dissertation is sporadically distributed across the ZCP. The investigations pertinent to the study area have been categorised to focus on key aspects discussed in this dissertation (i.e. geology, hydrogeology, surface water – groundwater interaction and anthropogenic impacts) and a review of available literature is presented below.

2.1 Geology

Commencing in the early 1970's, Hobday and Orme (1974), Maud and Orr (1975); Hobday (1979); Maud (1980) and Patridge and Maud (1987) undertook intensive geological mapping across the ZCP. According to the findings of these investigations, the ZCP is underlain by a Pre-Cambrian granitoid basement. The granitoid basement is exposed at a locality situated south of St. Lucia and is expected to occur at a depth of 1,000 mbgl along the coastline.

King (1972) reported that the Lebombo Group is a volcanic assemblage of felsic and mafic rocks. The Lebombo Group which signified the end of the fragmentation of Gondwanaland Land in the Jurassic is associated with tectonic uplift. Dipping eastwards, the volcanic rocks envelope a major fault and therefore underlie the Cretaceous and Cenozoic stratigraphy of the ZCP.

According to Dingle *et al.*, (1983), Mesozoic sediments deposited along the north-south trending coastal belt unconformably overlie the Lebombo Group. Hobday (1979) indicated that the Zululand Group displayed a distinct upward fining sequence of deposits ranging from basal pebble conglomerates to cross-bedded sands, marls and eventually silts which are indicative of rapid reduction of flow energy into distal fan braided channels.

Maud and Orr's (1975) research in Cenozoic geology suggested that the continental shelf was uplifted for a period of approximately 30 million (Ma) years and was subject to erosion prior to being inundated. This transgression prompted the deposition of the basal stratigraphic unit of the Maputaland Group. Achieving a cumulative thickness of 250 m, the Maputaland Group is a product of several episodes of marine transgression and regression.

The geology of the Uloa Formation was successively examined by Maud and Orr (1975), Worthington (1978) and eventually by Lui (1995). These authors' described the Uloa Formation as a sequence of calcified coquina conglomerate overlain by calcarenite. The deposition of these lithologies illustrates sea level fluctuation as the coquina conglomerate is typical of deep marine environments in comparison to the upper calcarenite which formed in shallow marine to aeolian depositional environments. The Uloa Formation is erratically

distributed across the ZCP and in certain places has been completely eroded due to karst solution weathering.

Maud and Orr (1975) indicated that the Umkwelane Formation overlies the karst weathered surface of the Uloa Formation. Similarly, the Umkwelane Formation is irregularly distributed and comprises coarse grain sedimentary rocks of typical beach environments that are overlain by calcarenite which confirms the hiatus between the Uloa and Umkwelane Formations, (Dingle *et al.*, 1983).

Research by Maud (1980); Hobday and Orme (1974); Worthington (1978) and Kelbe and Germishuyse (2001) on the Port Dunford Formation indicated that in comparison to the Uloa and Umkwelane Formations, it is present beneath most of the coastal barrier complexes. The basal rocks consist of coarse beach rocks overlain by the Upper Formation. The Upper Formation comprises the "Lower Argillaceous Member" that is dominated by thick marine and terrestrial mud with abundant mammalian fossils followed by the "Lignite Bed" and eventually capped by the "Upper Arenaceous Member" comprising sandstone with large scale cross-bedding.

Studies by Hobday and Orme (1974) suggested that the ZCP was extensively covered by the Kosi Bay Formation which comprised semi-consolidated orange to grey, weathered sand dunes with intercalated lenses of clay and lignite that overlie the Port Dunford Formation. These wind deposited sand formations achieved a thickness of 15 m.

Worthington (1978) indicated that the Kwabonambi Formation is unconsolidated to loosely consolidated deposits which formed on account of marine regression. On coastal outcrops in the Richards Bay area, the Kwabonambi Formation is dark brown and is significantly enriched with heavy mineral deposits than that present in the Kosi Bay Formation, (Maud and Orr, 1975).

Maud (1980) referred to the Kwabonambi and Sibayi Formations as the cover sands of the ZCP as they consisted of medium, well rounded grains. Hobday (1979) described the Sibayi Formation as a homogenous calcareous aeolian deposit that accretes to a height of 120 to 170 meters above mean sea level (mamsl). The Sibayi Formation is manifested along the coastline as north-south orientated dune cordons which achieve stability by virtue of dense vegetation.

Cognisant of the research discussed above, Watkeys *et al.*, (1993) discussed the role of geology in the development of Maputaland and explored the economic feasibility of the Maputaland Coastal Plain. Based on the findings of his study, the only economically viable natural resource for the area lay primarily in the heavy minerals of the Holocene coastal dunes. These coastal dunes separate the coastal Lake Sibayi and the estuarine linked lake systems such as Kosi and Lake St. Lucia which are segmented and form several smaller

lakes. Also, the coastal plain is ecologically diverse due to its prominent east-west variation in climate and geology thus resulting in establishment of several high profile conservation and tourism areas.

The localised occurrence of some geological formations in conjunction with lithologies which were difficult to accurately quantify on account of similar geological features with the adjacent lithologies, prompted a reevaluation of the lithostratigraphy proposed for the Maputaland Group. Regional mapping and or reassessment of the stratigraphy was undertaken by Botha (1997) and Maud and Botha (2000).

Botha (1997) suggested that the Sibayi Formation was the remnants of alluvial sedimentation which were the product of amalgamation of multiple high coastal dune cordons that restricted connection with the Indian Ocean.

The detailed regional mapping prompted research into the establishment of alternative relative and numerical dating techniques which were undertaken by Botha and Porat (2007). The calculation of the soil development index for layers which were sampled from hand augered holes and rare exposures was used in conjunction with infrared stimulated luminescence. These techniques assisted in the differentiation of dune systems and aeolian sand bodies. Their studies provided further insight into the dune morphology and pedogenic processes which occurred since deposition and also highlighted potential localised surficial reworking.

Porat and Botha (2008) expanded on the relative age relationships of the Quaternary parabolic, hummocky dunes, sand mega-ridges and the coastal barrier dune cordon. Using infrared stimulated luminescence, they contextualised the ages of the regional stratigraphic formations. The study highlighted that wind direction and strength were the principal factors controlling dune development and that a unidirectional wind regime resulted in the formation of elongated parabolic dunes. Sand mobility and parabolic dune migration into estuaries in the Holocene was vigorous enough to impede the marine links of the estuaries. This resulted in the formation of coastal lakes such as Lake Sibaya, Lake Nhlange and Lake Bhangazi.

They further hypothesised that expansive wetlands, hygrophilous grass and seasonal pans in the ZCP were characterised by a seasonally perched groundwater table typically associated with the clay enriched Kosi Bay Formation. In addition, the reduction of the sandy cover was attributed to the climatically controlled vadose zone fluctuations and associated variations in climatic conditions and vegetation cover.

The geology of the ZCP plays a pivotal role in the underlying aquifer's hydraulics (transmissivity and storage) and significantly influences groundwater chemistry. Therefore, the geology of the ZCP is thoroughly examined and pertinent geological information relating

to the study area, which has emanated from the literature review, is comprehensively discussed in Section 3-7 of this dissertation.

2.2 Hydrogeology

Worthington (1978) undertook a comprehensive geophysical survey of an area of approximately 200 km² in the vicinity of Richards Bay, an industrial town which has grown exponentially to date. Worthington's integrated geophysical and hydrogeological investigation provided early insight into the distribution and dynamics of the respective aquifers. Based on the findings of the geo-electrical survey and data derived from several boreholes, the Richards Bay area is underlain by Cretaceous aged siltstones which act as an impermeable boundary and are therefore regarded as the hydrogeological basement of the ZCP.

The major aquifer for the area comprises the discontinuous and sporadically distributed Miocene coquina and calcarenite which attained thicknesses of >20 m in certain areas. Aquifer parameters such as the storage coefficient and horizontal hydraulic conductivity were calculated at 6×10^{-4} and 2.5 m/d, respectively while transmissivity was highly variable. Mean Total Dissolved Solids (TDS) concentrations were at 350 ppm and generally good water quality was reported for the major aquifer.

The sequence of fine grain sands intercalated with clay and lignite represent the Pleistocene leaky aquitard which exhibits a bayesian relationship. In elevated areas the groundwater table is relatively deep due to a significant unsaturated profile while in low lying areas, the groundwater table is extremely shallow.

Worthington also highlighted significant subsurface recharge to the Mzingazi catchment. Mean Annual Precipitation (MAP) was estimated at 24% of recharge, baseflow contribution was c.80,000 m³/day and therefore significant groundwater seepage occurred.

Campbell *et al.*, (1992) collated information on the magnitude and importance of coastal aquifers in Southern Africa. The study was based on Cenozoic deposits and identified twenty four major coastal aquifers. Studies on the unconsolidated coastal aquifers revealed that these aquifers were capable of yielding between 5 to 30% of the gross volume of water stored in the aquifer and that recharge to the coastal aquifer was predominantly via direct infiltration of rainfall (8 to 30% of MAP) and seepage from surface water bodies.

Seepage from the aquifer recharged several surface water bodies as discharge was elevated along the shoreline and decreased offshore. Between 40 to 90% of the total flow usually occurred within 100 m of the shore whereas in the case of estuaries, groundwater discharge occurred within 30 to 100 m from the banks. A high proportion of hydrophytes were indicative of groundwater discharge.

King (1997) focused on the various aquifer types in KwaZulu-Natal (KZN). Based on King's findings, secondary aquifers were abundant in the province with the primary aquifer only occupying 13% of aerial extent of KZN of which 9% of the aquifer underlay rural areas.

Low permeability in the Kosi Bay and Port Dunford Formation was attributed to the fine grain size. This functionality increased the storativity of the aquifer and contributed towards sustaining the underlying Uloa Formation which had the highest the groundwater potential. High borehole yields in the Uloa Formation were a function of lithology thickness and degree of weathering (karstification). In comparison to the extensive fine grain sands, boreholes intercepting the coarse grain paleochannel deposits were typically high yielding.

The Berea-type red sands have low groundwater potential as it occurs on the dune ridges. However groundwater can be encountered in areas where the Berea-type red sands overlie bedrock at shallow depths. In this scenario, the Berea-type red sands does not constitute the aquifer but serves as a storage media to the more permeable contact zone.

Argillaceous rocks of the Zululand Group typically have low permeabilities and groundwater potential as groundwater was typically saline. Salinity was attributed to the marine deposited siltstones and therefore; groundwater had to be adequately treated prior to being suitable for potable use.

Using a numerical model, Nomqophu (1998) examined groundwater contribution to Lake St. Lucia and its ability to sustain the surrounding ecosystem. The study deduced that in comparison to the eastern shore region, the western shore area of Lake St. Lucia was hydraulically different. This contrast was attributed to the several rivers that emanated from the Lebombo Mountains and discharged into the lake's catchment. The numerical model suggested that the groundwater contribution (baseflow component) was responsible for sustaining the lake in periods of drought. Numerical simulations indicated that baseflow contribution in the Mpate catchment could be as high as $4 \times 10^6 \text{ m}^3 / \text{year}$ and therefore played an integral role in recharging the lake.

The model simulations for the Hluhluwe catchment further highlighted the importance of groundwater contribution as groundwater comprised >86% of the total annual discharge of $12.3 \times 10^6 \text{ m}^3/\text{year}$ measured at the Hluhluwe River mouth.

In an attempt to refine the conceptual model of the primary aquifer, Meyer *et al.*, (2001) undertook a study to assess the geohydrological conditions of the ZCP. Geological mapping was undertaken by utilising the electrical resistivity and electromagnetic geophysical techniques to establish the thickness and lateral extent of the geological formations.

The study reported that the Miocene succession was regarded as the major aquifer as borehole yields of 25 L/s were recorded in areas where this layer was >20 m thick. Porosity values were recorded at an average c.23% for the Holocene sands, c.31% for the Port Dunford Formation and >50% in the Uloa Formation. Hydraulic conductivities calculated ranged from 0.87 m/d (older aeolian sands) to 15.6 m/d (cover sands).

The study revealed that a groundwater divide roughly parallel to the coast was present. A rainfall - recharge relationship was established as recharge (percentage of MAP) was significant along the coast (18% recharge of MAP) and decreased inland (5% recharge of MAP).

Overall, water quality was generally good as electrical conductivity (EC) was reported at <100 mS/m. However regional geological formations have influenced the chemical signature of the groundwater. The effect can be observed in the boreholes that intercepted the low permeability Cretaceous siltstones as these boreholes had extremely poor groundwater quality and TDS was recorded at >8 000 mg/L.

Kelbe and Germishuys (2001) undertook a geohydrological study of the primary aquifer in the Richards Bay area. Their study used a numerical model to determine the hydraulics of the primary aquifer and examined the processes governing the functioning of water resources associated with the groundwater environment. Based on their findings, the surface hydrology of the Richards Bay area was classified into four categories which are summarised below:

- Mhlatuze River which is sustained by the Nseleni, Mfule and Mhlatazana Rivers and is regulated by the Goedertrouw Dam has been subjected to extensive artificial modifications and presently comprises two compartments viz. the Richards Bay Harbour in the north and its natural estuary in the south.
- Coastal Lakes comprising Lake Nhlabane, Mzingazi and Cubhu. These lakes are characterised by simultaneous recharge and discharge via different portions of the lake bed to the alluvial aquifer and may possibly have direct interaction with the underlying shallow aquifer. Recharge to these coastal lakes occurs via direct infiltration of precipitation, stream flow, runoff from riparian zones and baseflow contribution.
- Off-channel lakes have formed in the lower reaches of the Mhlatuze floodplain on account of the Mhlatuze River being choked with sand bars. The off-channel lakes are marked by shallow soils overlying the granitic basement. Discharge of the off-channel lakes are predominantly through surface runoff and baseflow to the Mhlatuze River.
- Combinations lakes such as Lake Nsezi which has a significant groundwater component. However, its operation is largely influenced by the Nseleni River which has its origin in a different geological regime.

Furthermore, several case studies undertaken over a three year period using numerical methods were presented however only relevant case studies have been selected for discussion purposes and are summarised below:

- Case Study 1: An assessment of the regional groundwater dynamics was undertaken to determine areas contributing to recharge of important water resources for the area. The network of lakes was believed to be an extension of the unconfined aquifer. The simulated flow configuration indicated that the lakes and rivers are separated by a groundwater divide which is assumed to be areas of recharge for the respective water sources. The flow pattern was subsequently used to determine the land use type that would potentially affect recharge, evaporation and pollution of the aquifer.
- Case Study 3: Focused on the role of groundwater seepage in the water balance of coastal lakes in the Richards Bay area. The hydrology of the coastal lakes was assumed to be controlled by the groundwater environment. The groundwater flow rates were in several orders of magnitude slower than that of the surface water flow rates. It was assumed that there was a rapid decrease in groundwater recharge to the lake with increasing distance from the shoreline. During periods of drought, there is a significant decrease in recharge to the lake where surface water - groundwater interaction is crucial in sustaining the water balance of the lake.

Cobbing *et al.*, (2008) provided a critical overview of transboundary aquifers shared by South Africa. The Mozambique or Zululand Coastal Aquifer was used as one of the examples to illustrate the heterogeneity in transboundary aquifer properties. According to the research findings, an area of approximately 50 km east-west and 120 km north-south in Zululand can be regarded as endoreic.

Isotope analyses across the plain have confirmed effective groundwater recharge values ranging between 5 to 18% of MAP. The primary aquifer generally had good water quality in comparison to the poor water quality of the Cretaceous age siltstones.

Several fresh water lakes which have emanated from the shallow groundwater levels, serve as vast potable water resources to the array of rural communities. The coastal dunes typically have a groundwater elevation of 20 mamsl. Fresh water seeps which occur along the coast are a function of the steep groundwater gradient along the coast (1:50 to 1:100).

The Uloa Formation, deemed the most productive aquifer, generated borehole yields in the magnitude of 30 L/s and transmissivity was expected to be $>1,000 \text{ m}^2/\text{d}$.

Schapers (2011) described the aquifer characteristics of the Airfield Aquifer (targeting the shallow unconsolidated sands of the Kwabonambi Formation) and the Thengane Well Field (targeting the deeper semi-confined Uloa Formation). These aquifers were utilised for the Kwangwanase (c.1,000 m^3/d) and Enkhanyazeni Groundwater Supply Schemes. The study

area was situated in the town of eManguze which is found in the northeastern extremities of the ZCP.

Based on geological data derived from the investigative boreholes, the Uloa Formation contained abundant shell fragments and displayed variation in vertical thickness over a 15 m distance thus confirming lateral and vertical heterogeneity of the geological formation. Dry boreholes were intercepted in areas where the calcrete was strongly cemented and dissolution channels were absent. Subsequent aquifer testing of the boreholes revealed that the deeper aquifer generally recorded late transmissivity (T) values of 99 m²/d while T-values ranging from 75 to 500 m²/d was calculated for the sands of the Kwabonambi Formation with several boreholes recording T-values >100 m²/d. Based on the above, the deep Uloa Formation in the study area was low yielding in comparison to the shallow aquifer.

The Kwabonambi Formation was typically dry in areas of high altitude while in low lying areas, it was a productive aquifer when these sands were >10 m thick. The relatively clean sands of the Kwabonambi Formation were characterised by shallow groundwater levels ranging from 0.90 to 4.50 mbgl and short residence times. The average safe abstraction rates in the shallow aquifer ranged from 5.25 to 10.78 L/s.

Water quality analyses (SANS 241 abbreviated analysis for drinking water quality) of the shallow and deep aquifer revealed that they were both enriched in sodium, potassium and calcium. However, samples collected from the deep aquifer had a significantly higher bicarbonate concentration in contrast to the shallow water samples which were deficient in bicarbonate thus confirming two distinct groundwater regimes and the influence of the host rock. EC ranged from 40 to 60 mS/m in the deep aquifer and at <20 mS/m in the shallow aquifer.

The Kosi Bay Formation had a high silt fraction and significantly lower T-values than that of the Kwabonambi and Uloa Formations. Therefore, it was considered a partial aquiclude that restricted both vertical and horizontal movement of groundwater which was attributed to the strong adhesive forces and low porosity associated with the clay and silt content.

Jeffares and Green (2012) documented the findings of the expansion of Department of Water Affairs (DWA) monitoring network in uMkhanyakude District Municipality. This investigation entailed the drilling and installation of monitoring wells in an attempt to augment the existing Lake Sibayi monitoring network and groundwater level monitoring data. The study identified four regional aquifers in the northern KwaZulu-Natal Coastal Plain which is summarised below:

- The younger Kwabonambi Formation (referred to as the cover sands) which was unconfined, high yielding and likely to be limited both laterally and vertically.

- The older Kwabonambi Formation which was associated with higher elevations and localized perched conditions.
- The silty sands and silt of the Kosi Bay Formation which typically had low transmissivity on account of adhesive forces and behaved as a semi-confined to confining layer.
- The calcareous sands, clay and gravel of the Umkwelane and Uloa Formation which was considered as a semi-confined to confined aquifer.
- The low yielding Cretaceous sediments associated with saline groundwater.

The geological formations intercepted during drilling comprised fine to coarse grain sand with sporadic silt and clay lenses. A downward coarsening, light greenish grey sand interlayered at the base with calcarenite was encountered in most boreholes and was assumed to be associated with the Umkwelane Formation. Calcrete containing shells was intercepted below the greenish grey sand horizon and was affiliated with the Uloa Formation.

A total of fifteen boreholes were selected for aquifer testing of which four boreholes intercepted the shallow aquifer while eleven boreholes intercepted the deep aquifer. Aquifer testing of boreholes intercepting the shallow aquifer indicated that pump rates ranging between 2.2 to 20 L/s were utilised and late T-values (calculated from the Cooper-Jacob method using the Flow Characteristics Software) ranged from 10 to as high as 5,544 m²/d with an average T-value reported at 1,489.4 m²/d. Pump rates utilised in the aquifer testing of the boreholes intercepting the deep aquifer ranged from 0.9 to 17.5 L/s and late T-values calculated ranged from 5.1 to 587.6 m²/d with an average T-value recorded at 115.9 m²/d.

The two production boreholes comprising the borehole in Manaba and Ntshongwe intercepted the deep aquifer. These boreholes generated yields of 7 L/s (likely to be associated with an estimated T-value of 100 m²/d) and 0.69 L/s (indicative of T-values in the order of 6.9 m²/d), respectively over a period of twenty four hours.

Water quality in both aquifers were generally good and suitable for human consumption however the disparity between the two aquifers was that the signature of the shallow aquifer was that of sodium, calcium and chloride while the deep aquifer was enriched with calcium and high alkalinity.

Based on the discussions above, it is evident that various investigations have attempted to understand the hydrogeology of the ZCP. Hydrogeological information pertaining to the lithostratigraphic units in the ZCP have therefore been concisely summarised and collated. Pertinent hydrogeological information derived from the literature survey is presented viz. in Chapter 5 which discusses the regional hydrogeology of the ZCP and in relation to the delineated hydrostratigraphic units (Section 6-3).

2.3 Surface Water – Groundwater Interaction

Kelbe and Germishuise (2010) investigated surface water - groundwater relationships in Maputaland. Several key concepts in understanding this dynamic relationship were thoroughly examined. To supplement the theory presented in the first part of the report, the second part of the report focused on seven case studies which investigated the relationship between the two regimes. Only relevant case studies and or concepts pertinent to surface water – groundwater interaction in the study area are briefly summarised below and used in discussions in this dissertation (Section 6-4).

- Case Study 1: ‘Simulating River Runoff Components Using Spatial Modelling Techniques’. This case study examined the runoff process in the Ntuze River catchment following a rainfall event. Analyses of hydrographs indicated that during dry periods or periods of little rainfall, the flow from streams and rivers were derived exclusively from groundwater (baseflow) however the baseflow component varied across the entire catchment.
- Case Study 4: ‘Estimation of Groundwater Contribution to River Flows in Maputaland Using Hydrograph Analyses Techniques’. This study examined the flow components of the Ntuze River and Alton Stream to determine the extent of groundwater contribution in two different hydrogeological regimes. Analyses of storm hydrographs highlighted the strong relationship between surface water and groundwater fluxes in shallow coastal environments as groundwater levels in the shallow borehole (BH3) situated in Alton mimicked the runoff trend while water levels in the deeper boreholes installed to 26 mbgl and 36 mbgl only peaked after 18 and 47 hours, respectively.
- Case Study 5: ‘Groundwater Recharge and Discharge Features for Shallow Primary Aquifers in Maputaland’. Shallow water recharge was regarded to be driven by gravity and was based on the extent to which rainfall was intercepted by the surface, infiltrated the soils and then percolated into the groundwater table. Simultaneous to this process, discharge was known to occur via evapotranspiration which occurred in the opposite direction and was governed by the vegetation type and atmospheric demand. Discharge from the primary unconfined aquifer occurred via lateral flow under a hydraulic gradient and through vertical fluxes during evapotranspiration. Three boreholes were installed to depths of 8, 24 and 36 mbgl. Analyses of the groundwater hydrographs indicated that the shape of the hydrograph varied significantly for the different depths and surface flow. Groundwater levels in the shallow aquifer showed a distinct peak in response to rainfall events which was not clear at greater depths. Recharge to the shallow aquifer was evident after 18 hours post the storm event.
- Case Study 7: ‘The Importance of Groundwater in Sustaining the Ecological Resilience of Lake St. Lucia’. Groundwater contribution to the lake was consistent but low in

comparison to its other recharge sources. In addition to other seepage zones along its shoreline, the dominant source of fresh water seepage was derived from the groundwater mound of the Embomveni Ridge which was situated at the Eastern Shore. Groundwater played a critical role in sustaining various species and ecosystems through the development of refugia sites during periods of drought when the lake was characterised by hyper saline conditions.

Parsons (2004) researched surface water – groundwater interaction in a South African context. According to this study, surface water – groundwater interaction provided a mechanism for chemical exchange between two distinct water bodies. However, this interaction was controlled by the elevation of the water level in the surface water body relative to that of the groundwater table.

Recharge in primary aquifers was estimated at 20% to 30% with specific yield ranging from 0.1 to 0.2 which were higher than secondary or fractured aquifers. Groundwater discharge was recorded in and around riparian zones and was illustrated by wetlands, springs and seeps where the perched aquifer discharged at the surface. In addition, the report also provided insight into the anthropogenic activities affecting surface water – groundwater interaction. Pertinent aspects documented in the report have been discussed throughout this dissertation.

Taylor *et al.*, (2006) investigated the groundwater dependent ecology along the shoreline of Lake St. Lucia. Lake St. Lucia is situated at the southern extremity of the Maputaland Coastal Plain and all the river catchments in the western interior drain towards the estuary. This drainage accounted for 45% of the freshwater input for the lake while 50% of freshwater input was derived from direct precipitation therefore groundwater contribution was regarded as very low.

During periods of drought, water loss via evaporation is replenished by sea water from the Indian Ocean which can often exceed 1 million m³/day. This augmentation can drastically increase the salinity of Lake St. Lucia and serve as the only source of replenishment during drought.

In 2001, approximately eighty groundwater dependant streams were identified however when the drought commenced in 2002, the groundwater dependant streams were drastically reduced to thirteen. The freshwater sustained an array of wildlife as these persistent creeks represented water sources for hippotamus and crocodiles, especially during the drought.

The quantification of surface water – groundwater interaction in the study area is achieved via the use of the Herold's Method and Saturated Volume Fluctuation. The discussions

emanating from the literature review are elaborated on in Section 6-4 to emphasise the relationship between surface water and groundwater and their inter-dependency.

2.4 Anthropogenic Impacts

Worthington (1978) analysed the pollution of aquifers in the vicinity of Lake Mzingazi. The study highlighted the geological and hydrogeological factors influencing the aquifer's susceptibility to pollution. A pollution vulnerability map for Lake Mzingazi was produced and highlighted five zones of high risks areas which were identified in the Miocene aquifer (<10 m thick), the Middle Pleistocene aquifer (>5 m thick) and the Upper Pleistocene aquifer (>10 m thick).

Campbell *et al.*, (1992) indicated that unconfined aquifers were extremely susceptible to pollution as they are composed of highly transmissive deposits with an absence of an overlying impenetrable layer. Pollution sources which adversely affect coastal aquifers are summarised below:

- Sources that are designed to discharge substances into the earth (pit latrines, septic tanks and waste water treatment works).
- Sources designed to store, treat and discharge substances (landfill and waste disposal sites, cemeteries, above and underground storage tanks and illegal dumping).
- Sources that are designed to retain substances as a consequence of planned activities (animal waste, irrigation, fertilizer or pesticide application and percolation of atmospheric pollutants).
- Sources discharging substances as a consequence of planned activities (animal waste, irrigation, fertiliser application and urban runoff).
- Sources providing a conduit for or inducing discharge through altered flow patterns.

Furthermore, the most apparent source of pollution was saline intrusion which can be exacerbated by human activities.

Cyrus *et al.*, (1997) study highlighted the dire consequences of salt water intrusion which was caused by inappropriate management of Lake Mzingazi coupled with influences from climatic variations. The devastating impacts of saline intrusion was documented in detail and shed light on the sensitivity of coastal ecosystems.

Meyer *et al.*, (2001) study revealed that shallow groundwater levels were responsible for sustaining several sensitive and complex ecosystems thus implying that anthropogenic impacts such as mining, afforestation, agriculture and the establishment of rural settlements would have adverse effects.

However on a regional scale, the major sources of pollution were considered to be land use which was driven by rapid population growth, the presence of commercial farms where fertilizers and pesticides were likely to be applied as well as the development of settlements in areas which would increase the generation of effluent. These land use hazards could be mitigated by restricting development to topographically high lying areas where the groundwater table would be expected to be deeper.

Another major source of pollution identified in this study was salt water intrusion. However, the study deduced that saline intrusion was unlikely to occur on account of the high sea level piezometric head characterising the coastal dune cordon.

Kelbe and Germishuyse (2001) in their numerical model case study also discussed the influence of land use variations on the water balance of Lake Mzingazi. According to their findings, impermeable road surfaces were associated with reduced recharge while deep rooting trees would decrease discharge and cumulatively have a significant impact on the water balance of a shallow unconfined aquifer. Evapotranspiration represented the largest impact to groundwater. Areas covered by mature forests, would also receive less recharge due to interception loss and evaporation.

DWAF (2002) discussed water quality issues in the Usutu to Mhlathuze Water Management Area (WMA). Based on this report, it was apparent that the anthropogenic impacts of the major land use zones comprising forestry, agriculture, mining, urban and industrial land use and rural practises were responsible for the water quality concerns documented in the WMA. Detailed discussions pertaining to the anthropogenic impacts of the respective land uses are discussed in Section 7-2.

Still and Nash (2002) investigated the anthropogenic impacts of pit latrines in rural communities. Several water quality trends were identified in the study which concluded that porous sands were effective in filtrating bacteria and that pit latrines and public water points affect the groundwater nitrate concentrations on a local scale.

Schmoll *et al.*, (2006) focused on the development of several strategies to protect groundwater by managing the quality of drinking water sources. The study provided an overview of various pollutant sources, transport mechanisms and their impact on the subsurface environment and human health. In addition, the study highlighted how anthropogenic activities introduced pollutants into the subsurface and the manner in which various aquifers responded to these pollutants.

The British Geological Survey (BGS), (2009) provided an information sheet pertaining to the impacts of agriculture. Agricultural groundwater abstraction for irrigation and the use of agrochemicals were identified as major anthropogenic impacts. The information sheet also highlighted the vulnerability of alluvial aquifers as areas underlain by permeable formations

and a shallow groundwater table were especially vulnerable to pollution due to the lack of impermeable layers which could potentially attenuate pollutants in the subsurface environment.

Kelbe and Germishuys (2010) case study highlighted the impact of historical land use comprising intensive sugar cane farming which caused extensive sedimentation of the Siyaya River and Estuary and eventually restricted flow into the estuary. Post 1990, the land use changed to forestry which resulted in a reduced sediment load however, historical sugar cane farming had a devastating impact on the catchment. Currently, excessive sedimentation supports the widespread growth of reeds. Most importantly, baseflow contribution to the Siyaya River and Estuary was drastically reduced and requires intervention by the Catchment Management Agency.

Schapers (2011) study suggested that the aquifers investigated are vulnerable to potential pollution arising from the nearby water treatment works and forest plantations. Iron oxide residue derived from backwashing of filters was unlikely to be rapidly transported from the settling ponds through the aquifer while fertilizers utilised in the forest plantations were also expected to potentially pollute the aquifer.

Mthembu *et al.*, (2012) investigated the anthropogenic impacts of industrial and agricultural activity on the Umhlathuze River situated near the industrial hub of Richards Bay. Surface water sampling and subsequent analyses revealed that that samples collected from areas affected by industrial activities were characterised by an acidic pH while nitrate, phosphate and ammonia were detected at high concentrations in areas situated close to agricultural practises. The study concluded that samples collected of the industrial effluent and agricultural waste at its discharge points along the Umhlathuze River exceeded the allowable limit stipulated in Department of Water Affairs Domestic Water Use Guideline (1996) however dilution of the respective pollutants of concern was detected upon entering the river.

Grundling *et al.*, (2013) assessed the distribution of wetlands over periods of water surplus and droughts using Landsat TM and ETM imagery for 1992 and 2008 (dry season) and Landsat ETM for 2000 (wet period). The study revealed the presence of several permanent groundwater fed wetland systems during dry periods. In addition, a combination of permanent and temporary wetlands was also identified during the wet periods. The comparison of the imagery collected in the winter and summer seasons further indicated that there was an 11% decrease in the distribution of wetlands in the dry periods while a 7% increase in grassland was noted over time. It is important to note that some areas which appeared to be grassland were actually wetlands and over the long term, the

occurrence of wetlands were reduced by anthropogenic impacts associated with agriculture, forestry and urbanisation.

The investigation undertaken by Brites and Vermeulen (2013) at the Nyalazi Plantation situated on the western shores of Lake St. Lucia highlighted the impact of the Pine and Eucalyptus plantations on the groundwater table. Groundwater monitoring via the installation of monitoring wells throughout the plantation revealed that the groundwater table in areas supporting the growth of natural vegetation (grass and shrubs) was very close to the surface (c.1.08 mbgl). The Pine plantation which was >28 years old and therefore regarded to be mature, was considered to have had minimal impact on the groundwater table which was at c.5.82 mbgl. Conversely, the Eucalyptus plantations of varying maturity had a profound impact on the receding groundwater table which declined between 10 m to 16 m over a period of 13 years whereas the groundwater table in the area overlain by indigenous trees declined between 4.5 m to 7.3 m over the same period.

Despite the operation of several mining companies in the study area (along the northern to southern coast of the town of Richards Bay), information pertaining to the anthropogenic impacts of mining is very limited due to the sensitivity of such operations and associated impacts. Therefore, a case study derived solely from Golder (2013) was used to discuss the anthropogenic impacts of mining.

Richards Bay Minerals (RBM) currently has several heavy mineral mining operations along the northern to southern coast of Richards Bay. The ore body which occurs in the dunes are mined by either dredge or dry mining however both techniques were associated with the destruction of the natural landscape. Despite RBM's success in dune restoration using the tailings derived from the mining process, several anthropogenic effects are far reaching even after the successful rehabilitation of the dunes with indigenous vegetation. These anthropogenic impacts largely comprise reduced soil fertility as the soils have low organic and nutrient content, limited water retention capacity and fluctuations in the groundwater table which is attributed to the mining process.

In this dissertation, anthropogenic activities were examined in relation to the quaternary catchments in the ZCP and the impacts of anthropogenic activities are presented using actual case studies. Therefore, detailed discussions emanating from the literature review are presented in Section 7-2.

3 Physiographic Description of the Zululand Coastal Plain

3.1 Location

The Zululand Coastal Plain is situated along the northeastern coastline of KZN and extends from Kosi Bay (in the north) which is along the Mozambiquean border (26°51'51.92"S and 32°11'05.43"E to 26°51'30.30"S and 32°53'27.53"E) and tapers towards the town of Mtunzini in the south (28°56'43.97"S and 31°47'54.27"E).

The warm Indian Ocean flanks the northeastern to southeastern peripheral boundary whilst the Lebombo Mountains, a linear belt of rhyolitic and basaltic extrusions, bounds the ZCP to the west, (DWAF, 2004). Therefore, the ZCP encompasses area of 6,000 km², spanning across 250 km north to south and 60 km east to west. However, the coastal plain continues to extend for >1,000 km into Mozambique thus representing the largest primary coastal aquifer in South Africa, (Meyer *et al.*, 2001).

To contextualise the location of the ZCP in terms of its setting in the province of KZN, most areas in the ZCP fall under the jurisdiction of Umkhanyakude District Municipality with the extreme southern portion occurring in the Uthungulu District Municipality, (UKDM, 2012). The location of the study area is shown in Figure 3-1.

The physical extent of the Zululand Coastal Aquifer can be defined by the boundaries of the W12F, W12J, W13B, W23C, W23D, W32B, W32H and W70A quaternary catchments as these catchments are principally underlain by the primary aquifer. The remaining thirteen quaternary catchments in the ZCP are underlain by components of either the *a3* or *a4* aquifer and *d1* aquifer types and therefore cannot be regarded as a true representation of the primary aquifer.

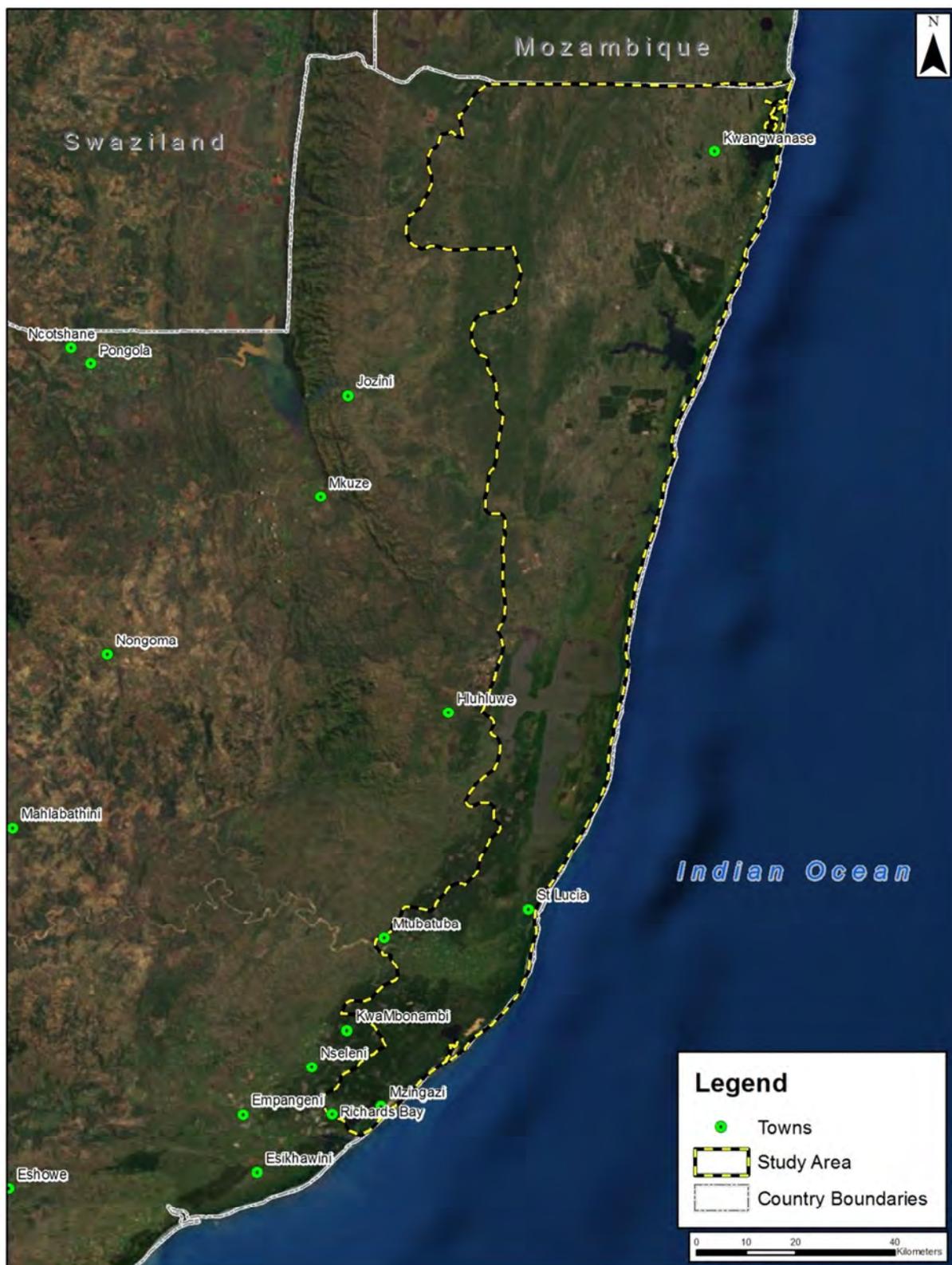


Figure 3-1: Aerial Photograph Showing the Location and Aerial Extent of the Study Area.

3.2 Topography

The topography of the western margin of the ZCP is characterised by the steep slopes of the Lebombo Mountain (situated at an altitude of c.651 mamsl) which gently flattens at the eastern foothills. Beyond the mountain foothills, the ZCP extends towards the eastern coastline with decreasing elevation (average of 15 to 20 mamsl). The terrain across the ZCP is gentle to undulating due to the presence of low sand ridges of 10 to 15 mamsl which are remnants of its geological era, (Porat and Botha, 2008).

However, the relatively flat topography across the ZCP displays an abrupt increase in surface relief closer to the coast on account of stacked dunes which are 1 to 2 km wide and represent the coastal barrier. The coastal barrier frequently achieves a height of up to 180 mamsl along the coastline and is marked by dense forest vegetation, (Sudan *et al.*, 2004). The series of dunes cordons forms river estuaries and creates isolated lakes and lagoons with restricted marine influence, (Taylor *et al.*, 2006). Thus, the landscape of the ZCP is a product of recurring marine transgressions and regressions which have manifested as prominent north-south orientated parabolic dune cordons that are synonymous with the configuration of the present coastline, (Hobday, 1979). A photograph of the north-south trending vegetated dune cordon is presented in Figure 3-2 (www.panoromia.com). Figure 3-3 shows the surface elevation of the ZCP and its surrounds.



Figure 3-2: Photograph Showing the Densely Vegetated North-South Orientated Parabolic Dune Cordons.

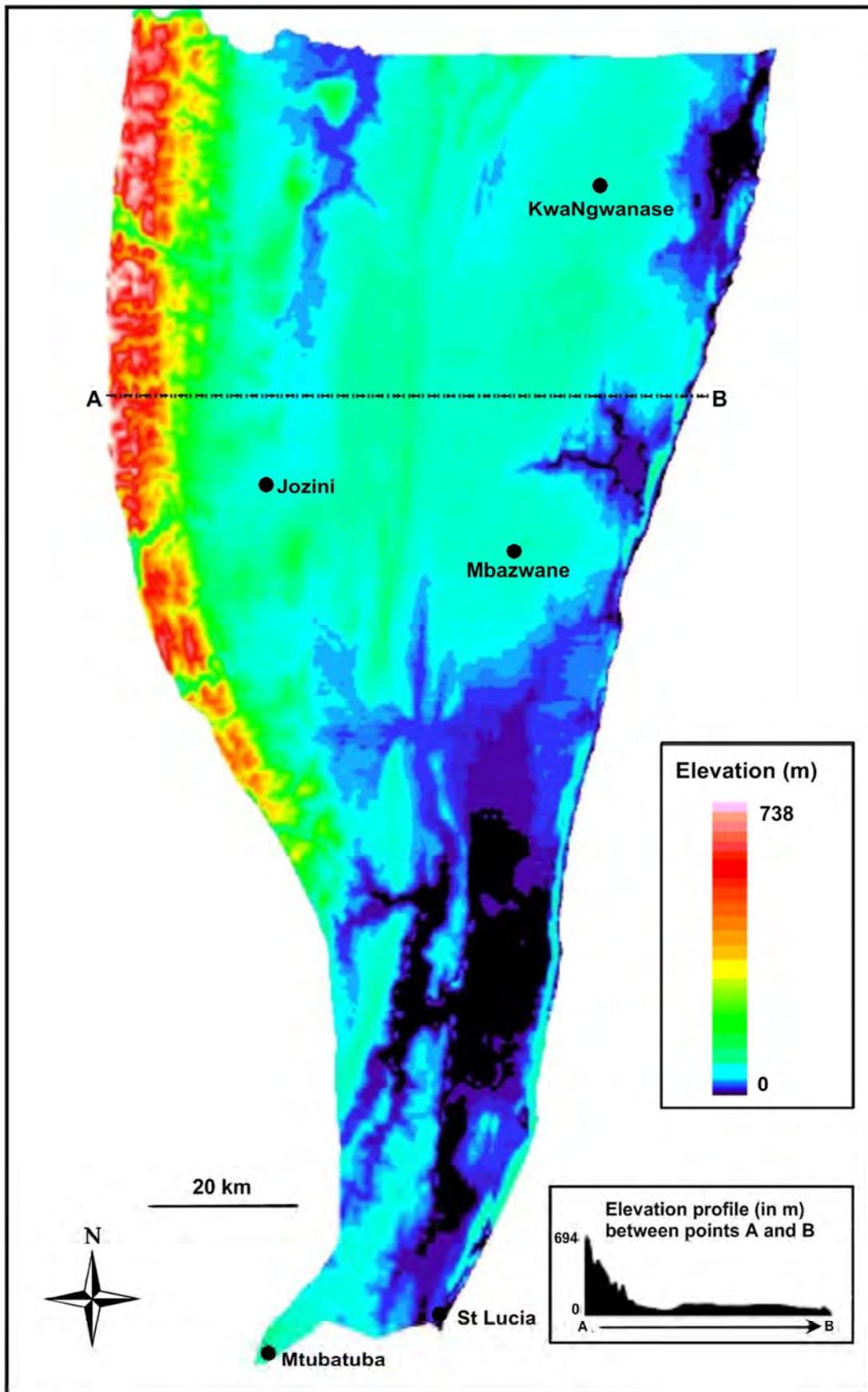


Figure 3-3: Digital Surface Elevation Model for Maputaland, (modified after Smith, 2001).

3.3 Climate

According to Hunter (1988), the ZCP has a humid subtropical climate. Maud (1980) indicated that temperatures along the Lebombo foothills ranged from 18.1°C to 26.3°C whilst varied temperatures ranging from 11.5°C to 28.7°C were experienced at the coast.

Atmospheric circulation is dominated by the South Atlantic and South Indian High Pressure Cells, (Hunter, 1998). Summer months are influenced by the northeasterly onshore winds while winter is dominated by the southwesterly offshore winds. The intensity of both winds are generally experienced along the coast however the dune cordons along the coastline influence the velocity and direction of the wind across the ZCP, (Ramsay, 1996).

Rainfall is the principal recharge mechanism for the primary aquifers in the ZCP and originates from both tropical and mid-latitude cyclones, (Kelbe and Germishuise, 2001). Convective thunderstorms which are the product of advection of warm moist air from the Indian Ocean and low level convergence are experienced in the summer months in which 80% of precipitation occurs, (Tyson, 1986).

Westerly waves originating in the temperate middle latitudes produce widespread frontal precipitation when they interact with the tropical depressions of the subcontinent causing severe thunderstorms and extensive flooding, (Kelbe and Germishuise, 2001).

Rainfall exhibits a prominent east-west gradient and decreases from 1,200 mm/a along the coast to <600 mm/a inland and then increases to 700 mm/a in the vicinity of the Lebombo Mountains, (Pitman and Hutchinson, 1975).

Evaporation rates are high throughout the year however the highest rates are experienced in summer and vary from a peak of 189.4 mm per month in January (6.1 mm/day) to a minimum of 82.3 mm per month (2.7 mm/day) in June which was measured in the Mkhuzi Game Reserve, (Watkeys *et al.*, 1993). Mucina and Rutherford (2006) indicated that the maximum potential evaporation was at 1,900 mm/a.

3.4 Oceanography

The northern KZN coastline represents a moderate to high energy wave environment and shows negligible seasonal influence with respect to wave height and direction. The coastline is dominated by large amplitude swells generated from the southeast however the low amplitude and of shorter duration swells arise from the northeast to eastern portion of the Indian Ocean, (Sudan, 1999).

The Richards Bay area is characterised by waves between 1 to 2 m in height although waves >2 m was observed at Cape St. Lucia and further northwards, (Sudan, 1999). Tinley (1985) indicated that the tidal and wave regime of the northern KZN coastline denoted a

wave dominated coastal sedimentary environment which was typical of a single beach berm.

The warm Agulhas Current is a major current which is produced by the anticlockwise circulation in the Indian Ocean and influences the coastline of KZN as it migrates south along the east coast of Africa from 27°S to 40°S latitudes, (Tyson, 1986). The source of water for the Agulhas Current is derived from the Mozambiquean Channel eddies and the Eastern Madagascar Current however the southwestern Indian Ocean sub-gyre provides the greatest source of water. The influence of the Agulhas Current is amplified by the narrow coastal shelf in the vicinity of southern Mozambique to Cape St. Lucia thus conveying clear, warm water rapidly down the eastern shoreline, (UKDM, 2012).

The temperature of the ocean surface which is a function of the Agulhas Current is estimated at 25°C (Figure 3-4) and therefore, influences the growth of fauna and flora. Threatened rare marine species and tropical to subtropical marine species seek refuge in these warm waters. Due to the warm temperatures, the growth of chlorophyll is restricted thus allowing for transparent water, (Porter, 2009).

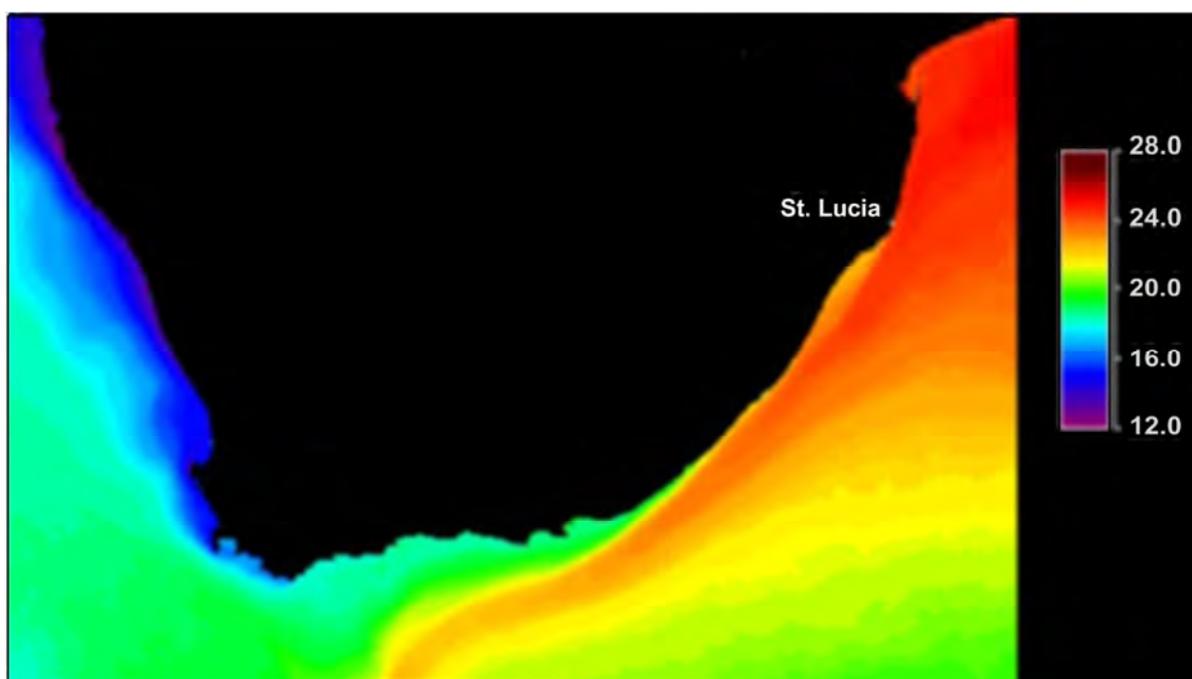


Figure 3-4: Average Sea-surface Temperature (°C) for Southern Africa where the Highest Temperatures are recorded along the East Coast of Africa, (modified after UKDM, 2012).

3.5 Vegetation

Vegetation growth is largely influenced by the physical and chemical characteristics of the environment. Therefore; the vegetation types of the ZCP can broadly be classified into two viz. the Coastal Tropical Forest and Tropical Bush (dune and coastal forests with swamp forests) and Savanna (thicket and grassland communities), (Acocks, 1988).

Due to the abundance in biodiversity, Tinley and Van Riet (1981) described five ecological regions in Maputaland which is summarised below and shown in Figure 3-5.

- **Lebombo Zone:** Vegetation of the Lebombo Mountains comprises mixed woodlands and grasslands in surficial soils. The deeper soil profiles support the growth of forests.
- **Cretaceous Zone:** Transition from the Cretaceous to Tertiary age formations is marked by woodlands on the mountain slopes which gradually changes to dense thicket and bushland at the valley base.
- **Alluvial Zone:** Occurs on Tertiary to Quaternary Age dunes and comprises bushveld interspersed with deciduous woodlands.
- **Coastal Plain Zone:** These areas are characterised by a shallow groundwater table. Hygrophilous coastal grasslands, swamps and forests are the dominant vegetation types. Progressively closer to the coast, dwarf woody endemics can be observed.
- **Coastal Dune Zone:** Delineates the eastern margin of the shoreline and encompasses the deep sand profiles of the dune cordons. The dune cordons are densely vegetated with forest canopies in excess of 30 m. The forests are associated with a relatively deeper groundwater table in comparison to the rest of the coastal plain area.

Maltby and Proctor (1996) defined peat as the brown to black organic rich soil (20% to 35% of dried organic matter) that is a result of the accumulation of decayed organic material in an anaerobic and low energy wetland. According to Grundling and Mazus (1998), the Maputaland Coastal Plain is endowed with approximately 60% of the peat deposits in South Africa. The peat deposits are distinguished by the presence of reeds, swamp forests and in some instances mangroves, (Grundling and Mazus, 1998) and typically occur in areas that are characterised by a perched groundwater table, (Mucina and Rutherford, 2006).

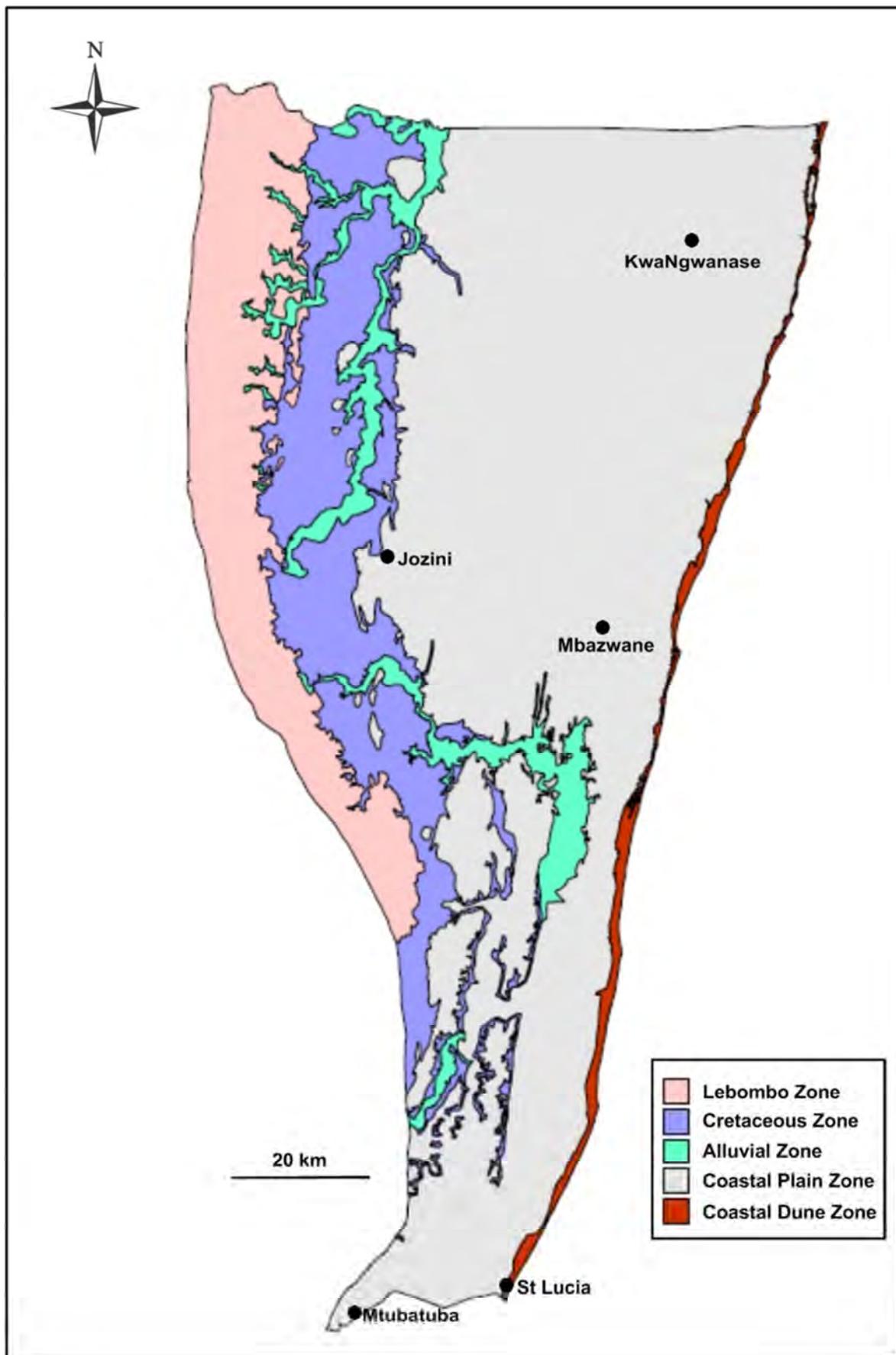


Figure 3-5: Ecological Zones of Maputaland, (modified after Smith, 2001).

3.6 Hydrology

The ZCP is situated in the Usutu to Mhlatuze Water Management Area (WMA). Rivers, lakes, estuaries and wetlands in the ZCP are key hydrological features and have varying degrees of groundwater dependency, (Kelbe and Germishuys, 2010).

The major rivers in the northern region of the Lebombo Mountain slopes are high energy rivers which are relatively linear and incised. These comprise the Usutu, Ngwavuma and Pongola River's. In contrast, the southern region of the Lebombo Mountain consists of the meandering Mkuze and Msunduze River's, (Watkeys *et al.*, 1993).

Several small streams and rivers are sporadically distributed along the coastline. They are predominantly groundwater dependant and are fundamental in sustaining various wetlands and lakes. In addition, there are numerous small, shallow pans that are irregularly distributed throughout the ZCP. These pans are affiliated with extensive flood plains and due to their shallow depth they are typically associated with a perched groundwater table, (Kelbe and Germishuys, 2010). The surface water resources and the quaternary catchments in the study area and surrounds are shown in Figure 3-6 and 3-7, respectively.

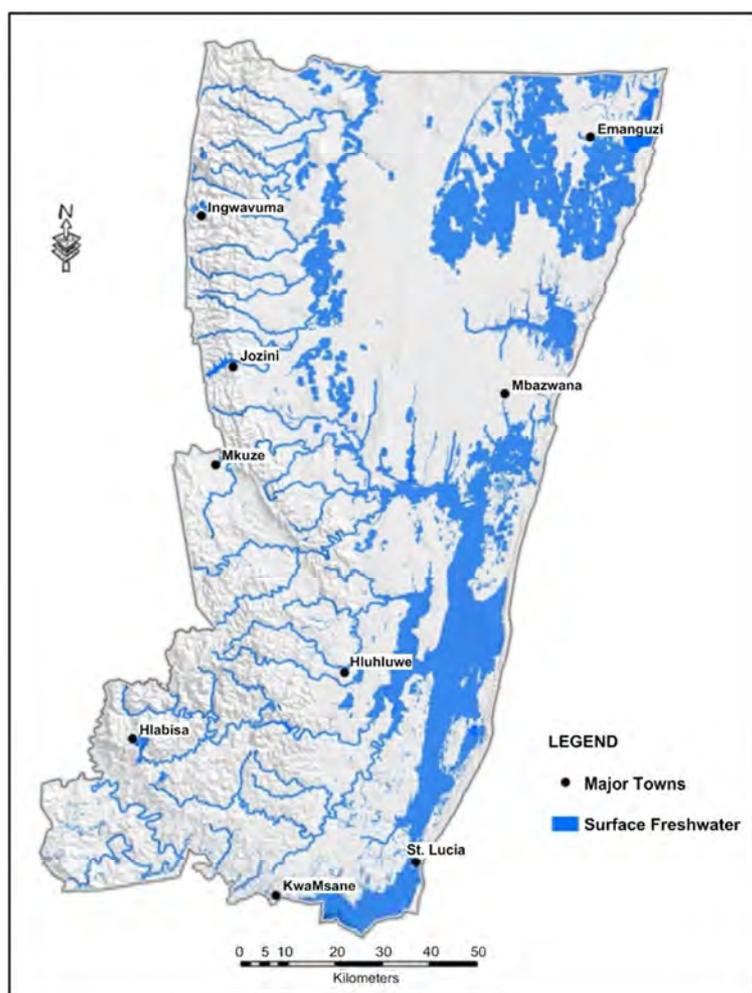


Figure 3-6: Surface Water Resources in the ZCP and Surrounds, (modified after UKDM, 2012).



Figure 3-7: Quaternary Catchments in the Zululand Coastal Plain.

Three major coastal lakes comprising Lake Sibaya, St. Lucia and the Kosi Bay Systems occur in the study area however, several smaller lakes are also present. The geomorphological features of these three major lakes are summarised below (from Wright *et al.*, 2000 unless otherwise stated).

- Lake Sibaya is a freshwater lake with a surface and catchment area of c.65 km² and c.536 km², respectively and has an average depth of 13 m. The lake is isolated from the Indian Ocean by the presence of the coastal dune cordons, (Miller, 1998). Recharge to the lake occurs via groundwater seepage and small streams. The lake is characterised by constantly fluctuating water levels which can be attributed to erratic groundwater recharge, evaporation and seepage loss from the dunes.
- The Kosi Bay System is an estuary or lake that situated in close proximity to the border of Mozambique and spans across an area of 44 km². The Kosi Bay System is poorly delineated due to the presence of several pans, swamps and marshes which surrounds its catchment of 540 km². The dominant recharge mechanism is via the shallow alluvial aquifer which is subject to seasonal influences as demonstrated by the lakes fluctuating water level. Surface drainage within the system is poor and can be attributed to the presence of the low permeability Kosi Bay Formation.
- The St. Lucia System is also an estuary or lake whose catchment varies from an estimated area of 8,900 km² to 9,065 km². The Mkuze River is the main river recharging the lake however additional flux from smaller rivers is noted. The lake is severely affected by salt water intrusion and evaporation. Evaporation accounts for a loss of $397 \times 10^6 \text{ m}^3/\text{a}$.

3.7 Geology

3.7.1 Pre-Cretaceous Geology

The Kaapvaal Craton represents one of the oldest plutons in the world. In relation to the study area, remnants of the 3.2 billion old Archaean age rocks are observed south of St. Lucia as the Empangeni Granite Suite. The Empangeni granite-gneiss basement which comprises potassic granitoids and amphibolites, was juxtaposed between the east-west crustal rifts resulting in the formation of the elongate fault block of the Ngoye Range, (King, 1972). It is assumed that the granite-gneiss surface declines in an east to southeasterly direction and can be expected to occur at an approximate depth of 1,000 mbgl at the coastline, (Maud and Orr, 1975).

In the Jurassic, fragmentation of the supercontinent, Pangaea, resulted in the formation of Gondwanaland. The subsequent rifting of Gondwanaland was marked by the widespread magmatism and north-south and northeast-southwest orientated normal fault blocks which formed the basement of the ZCP. The Indian Ocean and the present phenomenon of sea floor spreading can be attributed to the rifting of Gondwanaland, (Partridge and Maud, 1987).

3.7.2 Lebombo Group

The volcanic deposits of the Lebombo Group (c.130 to 180 Ma) signified the termination of Karoo sedimentation. The eruption of low viscosity basic lava formed alternating cycles of massive and amygdaloidal basalts which accumulated to several thousands of meters of basaltic deposits. The basalts gently dip at angles between 5° and 15° in northern KwaZulu-Natal thus forming the Natal monocline with sporadic attendant faulting, (King, 1972).

The subsequent phase of volcanism was violent, resulting in explosive eruptions of rhyolitic lava and the deposition of c.4,800 m thick pyroclastic debris, (Tankard *et al.*, 1982). According to McCarthy (1979), the formation of rhyolites can be attributed to the differentiation and assimilation of the basaltic magma with Karoo sediments and Archean rocks which culminated in the eruption of acidic lavas. Successive uplift, forming the Lebombo Mountains, and faulting eventually separated Africa and Antarctica, (Tankard *et al.*, 1982).

The oldest rocks exposed in Maputaland are the Jozini Formation rhyolites (c.179 Ma) of the Lebombo Mountain which are observed west of the ZCP, (Alssop *et al.*, 1984). Conglomerates of the Msunduze Formation separate the younger basalts of the Movene and Mpilo Formations from the older rhyolites, (Dingle *et al.*, 1983). The upper surface of the volcanic basement contains pyroclastics, rhyolites and trachytes of the Bumbeni

Complex (c.130 Ma), (Alssop *et al.*, 1984). The volcanic assemblage envelopes a major fault and dip eastwards thereby underlying the Cretaceous and Cenozoic sediments of the ZCP, (King, 1972).

3.7.3 Zululand Group

The sediments of the Zululand Group form a segment that thickens from surface along the Lebombo Mountains to c.3 km along the coast which suggests asymmetrical opening of the Indian Ocean, (Maud, 1980). Hobday (1979) indicated that the Zululand Group displayed a distinct upward fining sequence of deposits ranging from basal pebble and conglomerates to cross-bedded sandstone, marls and eventually siltstone which are indicative of rapid reduction of flow energy into distal fan braided channels. Meyer *et al.*, (2001) reported that the Cretaceous Formation dipped at an angle of 3° - 5° with its strike direction roughly parallel to the coast.

Cretaceous aged sediments of the Zululand Group unconformably rest on the igneous basement rocks as the horst and graben structures. The horst and graben structures are associated with the fault blocks created during the fragmentation of Gondwanaland, (Partridge and Maud, 1987).

The Cretaceous siltstones represent the lower boundary of the ZCP and are characterised by significant palaeochannels which were incised by alluvial processes under different marine regimes, (Kelbe and Germishuise, 2000).

During the Cretaceous period, the continental margin was generally submerged as a shallow continental shelf. Therefore, the overlying Mzinene Formation was characterised by the deposition of shallow marine glauconitic silts and sand which contained shelly concretions, (Dingle *et al.*, 1983). The dark olive-grey to greenish-grey coloured siltstones are relatively uniform with sporadic thin clay lenses and bands of hard sandy limestone, (Meyer *et al.*, 2001).

The overlying St. Lucia Formation is poorly exposed and comprises a basal conglomerate bed with an upward fining succession of glauconitic silts, sands and interbedded hardgrounds. The strike of the St. Lucia Formation is almost parallel to the coastline and the dip is calculated towards the southeast in the Richards Bay area, (Maud and Orr, 1975). Fossils (ammonites, bivalves, gastropods and foraminifera) and calcareous nodules are abundant in this formation, (Kennedy and Klinger, 1975) which is estimated to be approximately 20 to 30 m amsl in the immediate vicinity of Lake Sibaya, (Pitman and Hutchinson, 1975). A regional geological map for the ZCP is shown in Figure 3-8.

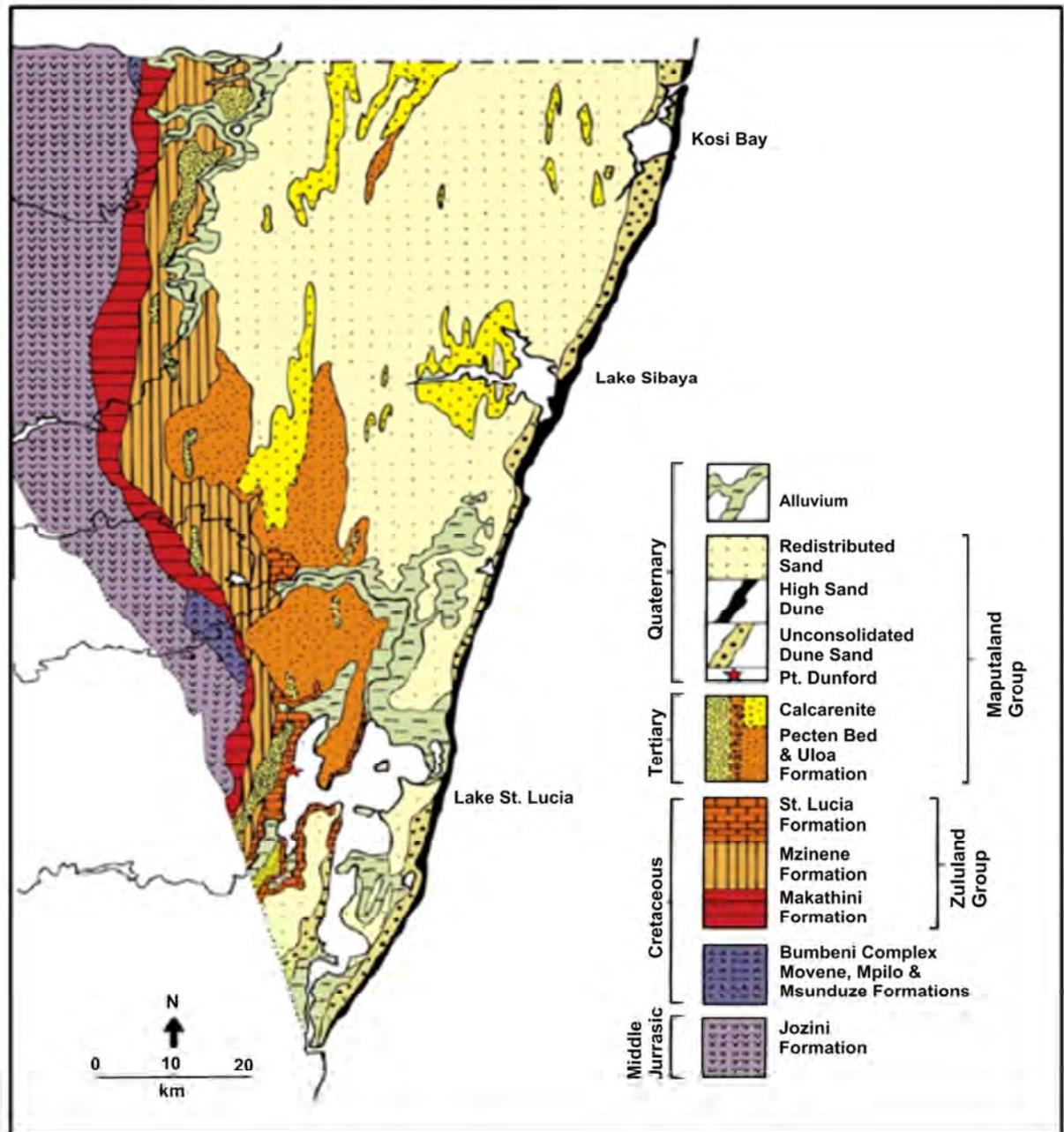


Figure 3-8: Regional Geological Map for the Zululand Coastal Plain, (Watkeys *et. al* 1993).

3.7.4 Maputaland Group

Following the deposition of the Zululand Group, the continental shelf was uplifted for a period of approximately 30 Ma years and was subject to erosion. The Zululand Group was subsequently inundated which allowed for the deposition of the first formation, the Uloa Formation, of the Maputaland Group, (Maud and Orr, 1975). The Maputaland Group comprises a series of lagoonal, fluvial, aeolian and shoreline to shallow marine deposits of the Late Miocene to Holocene Age and is cumulatively 250 m thick,

(Dunlevey and August, 2010). The stratigraphy of the Maputaland Group is tabulated in Table 3-1 and shown in Figure 3-9.

Table 3-1: Stratigraphic Column for the Maputaland Group (referenced from both Watkeys *et al.*, (1993) and Meyer *et al.*, (2001)).

Age (Ma)	System / Period	Series / Epoch	Group	Formation	Lithology
0.1		Holocene (recent)	Maputaland		Alluvium, dune, aeolian and beach sands.
<1.6	Quaternary	Pleistocene		Berea	Sand, red clay and rich sand.
				Bluff	Calcareous sandstone.
				Upper Port Dunford	Sand and sandstone.
					Lignite.
Lower Port Dunford Formation	Clay rich sandstone.				
1.6 - 65	Tertiary	Late Miocene to Pleistocene	Uloa	Calcareous sandstone and coquina.	
		Palaeocene	St Lucia	Siltstone and sandstone.	
65 - 146	Cretaceous	Late Cretaceous	Zululand	Mzinene	Glauconitic siltstone.
		Early Cretaceous		Makatini	Conglomerate, sandstone and siltstone.
146 - 208	Jurassic	-	Lebombo	Mpilo or Movene	Amygdaloidal trachybasalt.
				Jozini	Rhyodacite and rhyolite.
				Letaba	Basalt and rhyolitic lava.

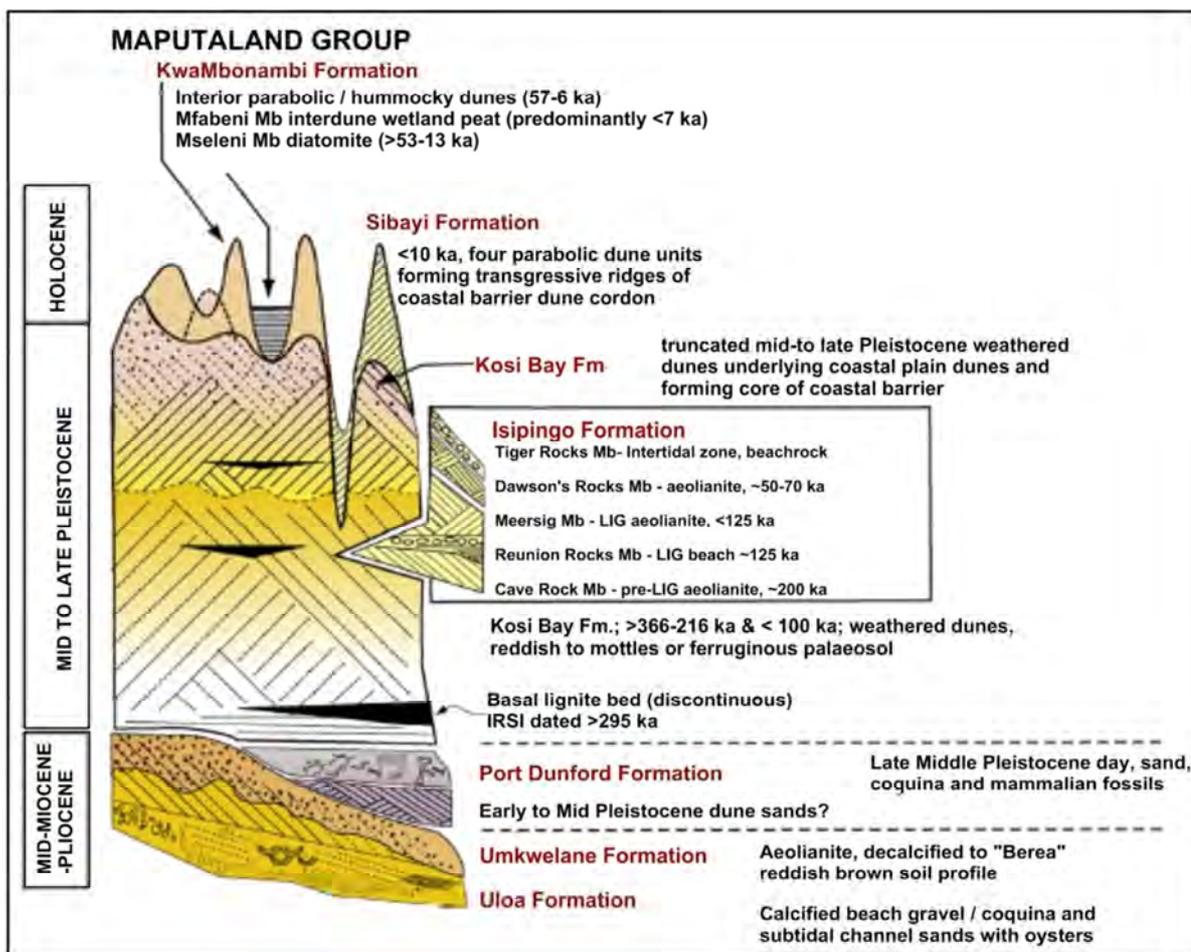


Figure 3-9: Schematic Representation of the Maputaland Group Lithostratigraphic Units Showing the Relationship between the Formations and Specific Sedimentary Unit. LIG is defined as the Last Interglacial Period, (Porat and Botha, 2008).

Uloa Formation

Deposition of the Uloa Formation occurred in the Late Miocene and extended into the Pleistocene. The Uloa Formation consists of a lower coquina and an upper calcarenite layer. The base of the Uloa Formation comprises c.2.5 m thick basal conglomerate bed which rests unconformably on the eroded surface of the St. Lucia Formation siltstones. The basal conglomerate which suggests deposition in deep marine waters is overlain by the Pecten Bed (glauconite rich and fossiliferous calcrudites) which is frequently referred to as the Coquina, (Maud and Orr, 1975).

The Pecten Bed is generally c.4.3 m thick and is indicative of shallow marine waters. The upper surface of the coquina limestone is yellow-brown in colour as it is highly leached and iron stained on account of karst solution weathering prior to the deposition of the calcarenite. In the type area, the Uloa Formation achieves a thickness of c.6.8 m, (Liu, 1995).

The calcarenite consists of a coarse grain, well-bedded lower portion which is typical of deposition in a shallow marine environment. The upper portion consists of aeolian deposits which display steep cross bedding. Overall, the calcarenite appears as a hard, light grey sandy limestone. The strike of the calcarenite is parallel to the coast with a slight southeastward dip, (Worthington, 1978).

Exposures of the Uloa Formation are observed at Uloa, Sapolwana along the Umfolozi Plain and at Lake View along the Pongola River, (Meyer *et al.*, 2001). Worthington's (1978) geo-electrical survey concluded that the Uloa Formation achieved thicknesses in excess of 20 m in certain areas. However, karst solution weathering has resulted in the erratic distribution of the Uloa Formation which in some places has been completely eroded. Generally, the Uloa Formation is approximately 6 m thick and its mode of distribution deemed complex, (Maud and Orr, 1975). The Uloa Formation generally occurs on the higher regions of the Cretaceous siltstone Formation, (Kelbe and Germishuys, 2000).

Umkwelane Formation

The Umkwelane Formation overlies the Uloa Formation and comprises a beach or marine succession of coarse grain sedimentary rocks overlain by aeolian cross-bedded hard, light grey calcarenites, (Maud and Orr, 1975). The Umkwelane Formation attains a thickness of c.4 m and is karstified on the upper surface, (Dingle *et al.*, 1983).

The transformation from beach or marine to an aeolian depositional environment confirms the hiatus between the Uloa and Umkwelane Formations. Both formations are erratically distributed across the ZCP, (Maud and Orr, 1975).

Port Dunford Formation

According to Hobday and Orme (1974), remnants of the Uloa and Umkwelane Formation are unconformably overlain by sediments of the Port Dunford Formation. The basal component of the Port Dunford Formation in the Richards Bay area comprises coarse beach rocks, (Maud and Orr, 1975).

Hobday and Orme (1974) indicated that the upper portion of the Port Dunford Formation constitutes a 10 m thick marine and terrestrial fossiliferous grey and black mud with sandy lamina often referred to as the "Lower Argillaceous Member". The "Lower Argillaceous Member" is overlain by a 0.2 m to 2.5 m thick lignite layer defined as the "Lignite Bed". A thin layer of marine sands marks the base of the "Upper Arenaceous Member" of the Port Dunford Formation. The basal unit consists of wash-over sands followed by a thick sequence of medium grain sands which exhibit large scale cross-bedding. Sporadic lenses of carbonaceous sand and lignite occur within this succession.

Maud (1980) and Hobday and Orme (1974) suggest that the Lower Argillaceous Member was deposited in transgressive conditions which is illustrated by the blue-grey mudstone

enriched in mammalian fossils. However, the Upper Arenaceous Member represents deposition during regression under littoral and sub-aerial conditions as demonstrated by the intermittent lignite beds and large scale cross-bedding. Worthington (1978) reported an average thickness of 20 m for the Port Dunford Formation.

Maud and Orr (1975) suggest that the Port Dunford Formation consists of laterally discontinuous layers of mixed facies and age. However, Kelbe and Germishuys (2001) believe that in comparison to the Uloa and Umkwelane Formations, the Port Dunford Formation is extensive and is present beneath most of the coastal barrier complexes.

Following deposition of the Port Dunford Formation, erosion, solution weathering and karst development ensued with a subsequent period of marine regression. Remnants of this period are manifested by the intense weathering of the Port Dunford Formation which formed the Berea-type red sand. The Berea-type red sands are enriched in clay which is a product of the weathering and oxidation of iron bearing silicate minerals. The deep red pigmentation of the formation can be attributed to the enrichment of haematite, (Meyer *et al.*, 2001). The high clay fraction suggests deposition via in-situ weathering rather than deposition via wind, (Worthington, 1978).

Kosi Bay Formation

The Kosi Bay Formation is assumed to cover most of the ZCP and comprises semi-consolidated orange to grey, weathered sand dunes with intercalated lenses of clay and lignite which overlie the Port Dunford Formation. The aeolian Kosi Bay deposit achieves a thickness of 15 m, (Hobday and Orme, 1974). Where the clay enriched Kosi Bay weathering profiles are exposed in broad bottomlands, the perched water table creates expansive wetlands as demonstrated by the Kosi Bay System and Lake St. Lucia, (Botha and Porat, 2007).

Isipingo Formation

According to Maud and Botha (2000), the Isipingo Formation which comprises calcified dunes and beach deposits formed in response to sea level fluctuations and are distributed along the eastern coastline. The Isipingo Formation forms the core part of the coastal barrier dune cordon, (Maud and Botha, 2000). However, the Isipingo Formation was not identified during Botha and Porat's (2007) extensive study of the Maputaland Coastal Plain.

Kwabonambi Formation

During the peak of the Last Glacial Maximum, marine regression exposed a substantial portion of the continental shelf. Therefore, the Kwabonambi Formation unconformably overlies the Kosi Bay and Port Dunford Formation's in the Richards Bay area. The Kwabonambi Formation encompasses decalcified dune sediments derived from the

alteration of older dune sands, inter-dune wetland deposits and freshwater diatomite accumulations, (Botha, 1997).

Worthington (1978) indicated that the Kwabonambi Formation comprises unconsolidated sands. On coastal outcrops in the Richards Bay area, the Kwabonambi Formation is dark brown, (Maud and Orr, 1975). Typically, the fine fraction is low in contrast to the abundance of heavy minerals which is significantly higher than that of the underlying Kosi Bay Formation, (Botha, 1997).

The morphology of the dunes of the Kwabonambi Formation comprise closely spaced, north-south orientated parabolic dunes, wind drift parabolic dune limb remnants and hummocky dunes, (Porat and Botha, 2008). Therefore, the low undulating topography in the vicinity of Lake Sibaya symbolises remnants of the relic dune cordons, (Wright, 1996). The hummocky dunes of the Kwabonambi Formation form surface relief of 10 m to 15 m above the ZCP. Drainage systems of the Sibaya, St. Lucia and Kosi Bay Systems have scoured these dunes with widespread ephemeral inter-dune wetlands and hygrophilous grass separating the dunes into discrete patterns, (Porat and Botha, 2008).

Sibayi Formation

The Holocene marine transgression inundated coastal valleys and lakes and is illustrated by the presence of beach ridges within coastal lakes and beach rock along the coast. The remnants of alluvial sedimentation which are the product of the amalgamation of multiple high coastal dune cordons that restricted connection with the Indian Ocean are referred to as the Sibayi Formation, (Botha, 1997).

The calcareous, relatively uniform aeolian deposit of the Sibayi Formation is underlain by boulder beds and pebbles and form north-south parabolic dune cordons, (Hobday, 1979). Porat and Botha (2008) indicated that the Sibayi Formation coastal barrier dune peaks between 120 to 172 mamsl along the eastern shoreline and comprises ascending parabolic dunes forming up to four composite traverses in some areas which serve to define the morphology of the present coastline (Figure 3-2). The dune cordons separate the high energy shoreline from the three major estuarine linked coastal lakes, (Watkeys *et al.*, 1993).

Maud (1980) referred to the Kwabonambi and Sibayi Formations as the cover sands of the ZCP which consists of medium, well rounded grains. Thicknesses of these sands range from 0.5 m to 3 m, (Hobday, 1976). The aforementioned sands are characterised by high permeability and porosity (Rawlins, 1991) and play an integral role in the hydraulics of the St. Lucia aquifer, (Nomquphu, 1998). Dense vegetation on the dune cordons provides stability and prevents collapse of the high aeolian deposits, (Maud, 1980).

Based on the discussions presented in this section and subsequent evaluation of boreholes logs recorded in the GRIP and NGA database's and reports from the private sector, the general depth of occurrence for the various stratigraphic units in the Maputaland Group are tabulated below.

Table 3-2: Categorisation of Geological Formations Recorded in Borehole Logs

Inferred Depth of Occurrence (mbgl)	Key Lithology Described in the Borehole Logs	Associated Stratigraphic Unit
0-19	Medium grain, loose unconsolidated sand.	Sibayi Formation.
0-37	Unconsolidated to loosely consolidated sand enriched in clay and silt.	Kwabonambi Formation
0-37	Silty sand and clay that occurs in association with lignite or peat.	Kosi Bay and Port Dunford Formation
6-42	Coquina (shells), calcarenite, calcrete and conglomerate.	Uloa Formation
12-48	Siltstone, marl and sandstone.	Zululand Group

4 Methodology and Approach

4.1 Methodology Adopted for the Dissertation

The literature survey detailed in Chapter 2 and elaborated on in Chapter 3 exposes the variety and degree of research undertaken in the ZCP. Further to this, the collection of hydrogeological data from the relevant databases comprising the National Groundwater Archive (NGA), Groundwater Resource Information Project (GRIP) and the Water Authorisations Registration Management System (WARMS) including the collection and interpretation of data from the private sector was undertaken in order to supplement the available literature sources. Based on the above, the methodology adopted for the study is outlined below:

- Collate all available and relevant data pertaining to this dissertation in a concise and accurate manner and where deemed necessary, use the available literature sources to supplement discussions in the dissertation.
- The delineation of hydrostratigraphic units will be undertaken to demarcate aquifers of similar character, behaviour and potential. The hydrostratigraphic units will be delineated utilising the methodology as defined by Vegter (2001). As Vegter's (2001) methodology forms an integral part of this dissertation, it is discussed in detail in Section 4-2.
- The geological information used to delineate the hydrostratigraphic units will be derived from the regional geology of the ZCP (Section 3-7 of this dissertation), boreholes logs recorded on the GRIP and NGA database as well as from available reports and is discussed in further detail in Section 4-3.
- As field aquifer testing was outside the proposed scope of work for the study, actual pump test data was unavailable for the calculation of aquifer parameters. Where relevant data was available, the calculation of aquifer parameters was based on the following assumptions:
 - Transmissivity (T): Where the maximum yield of the borehole was available, transmissivity values were either derived from a literature source or calculated on the basis of a qualified guess where $T (m^2/d) = 10 \cdot Q$. 'Q' represents discharge and is measured in L/s (Van Tonder *et al.*, 2002).
 - Hydraulic conductivity (K): In the absence of pump test data, hydraulic conductivity, porosity, storativity and specific yield values were derived from literature sources where actual borehole testing was undertaken.
- Surface water – groundwater interaction (the interaction of groundwater with the adjacent rivers, wetlands and lakes) will be evaluated using the Herold's Curve Fitting

and the Saturated Flow Volume (SVF) Method. In addition, flow data from the Department of Water Affairs gauges' in the study area will be used to determine the degree of surface water (river) - groundwater interaction.

- The methodology for the delineation of anthropogenic activities is elaborated on in Section 4-4.

4.2 Vegter's (2001) Methodology

According to Vegter (2001), South Africa is a geologically complex country and therefore, the division and delineation of sub-areas that have uniform distribution allows for an effective description of groundwater occurrence that would assist in establishing guidelines and cost-effective siting of boreholes. Utilising the water-bearing potential of geological formations, the water-bearing¹ units were classified into two groups¹ viz. primary openings and secondary openings.

The purpose of delineation of groundwater regions is to obtain a certain degree of consistency with regards to lithostratigraphy, physiography and climate. However, Vegter (2001) emphasised that the delineation of groundwater regions must be based on geological formations as geology principally influences the groundwater chemistry. In addition, Vegter (2001) also stated that the occurrence and availability of groundwater at any locality was governed by the following factors:

- The storage and transmissivity of the geological formation.
- The volume and frequency of recharge.
- The rate of groundwater movement to discharge points or areas.
- The rate of groundwater discharge as springs and seepage in effluent streams.
- Loss via evapotranspiration (ET).

Taking the above factors into consideration, Vegter (2001) used the following criteria to sub-divide and delineate groundwater regions in South Africa:

- Lithostratigraphy:
 - Type of openings (primary or secondary).
- Physiography:
 - Topographic relief would influence the hydraulic gradient as transmissivity was expected to generally decrease with depth.

¹ Note: Vegter (2001) refrained from using the term 'aquifer' as it described that part of a body of water-bearing formation that is capable of transmitting groundwater rapidly enough to directly supply a spring or borehole. The term 'water-bearing' described saturated material consisting of highly variable proportions of permeable (aquifer), semi-permeable (aquitard) and impermeable (aquifuge) material.

- Also surface configuration would influence the loss or discharge of groundwater specifically at low topographic elevations.
- Climate:
 - Recharge which is a function of rainfall (volume, frequency, intensity and temporal distribution), availability of surface water, land surface configuration, soil and vegetative cover and subsurface moisture retention.
 - Evapotranspiration which would equate to loss of effective recharge.

Based on the discussions above, Vegter (2001) delineated a total of sixty-five groundwater regions for South Africa. Of these 65 groundwater regions, only four groundwater regions representative of extensive primary formations (porous or alluvial aquifers) were identified and are listed below:

- Region 60: Die Kelders Embayment situated in Western Cape.
- Region 61: Bredasdorp Coastal Belt situated in Western Cape.
- Region 62: Stilbaai Coastal Belt situated in Western Cape.
- Region 65: Northern Zululand Coastal Plain situated in KwaZulu-Natal.

4.3 Delineation of Hydrostratigraphic Units using Geology

The hydrostratigraphic units were delineated utilising the methodology defined by Vegter (2001) (discussed in Chapter 4-2) and field geological data. Geology plays a vital role in influencing groundwater hydraulics, chemistry and storativity of aquifers; therefore a detailed description of the geology in the area was presented in Section 3-7.

For the purpose of this dissertation, geological data used to delineate the hydrostratigraphic units were derived from Section 3-7, boreholes logs recorded on the GRIP and NGA database's and reports from the private sector. Thereafter, the geological data from the abovementioned borehole logs were consolidated into a single geological database.

Evaluation of the geology recorded in the borehole logs suggests overlap or transition of geological formations at various depths. Frequently where this is known to occur, an actual or defined depth is not stated.

Thereafter, geostatistical analysis of the geological database (discussed above), for the study area was undertaken to identify hydrogeological trends. The statistical analysis undertaken of the geological database is detailed below:

- Borehole yields in various lithologies.
- Distribution of boreholes based on depth.
- Borehole depth versus static water level analysis.

- Calculation of aquifer parameters by using the firm yield model.
- Geochemical analysis to assess water quality trends.

Using the geological database created, statistical analyses discussed above and Vegter's (2001) methodology, similar geological formations were consolidated and used to laterally and vertically delineate hydrostratigraphic units. Hydrogeological properties for the respective hydrostratigraphic units are then discussed using existing data (on account of limited borehole pump test data which is discussed in Chapter 6-3).

4.4 Methodology for the Delineation of Anthropogenic Activities

Land use plays a fundamental role as it directly influences the occurrence of anthropogenic impacts hence; the anthropogenic activities for the study area were delineated on the basis of land use and quaternary catchment boundaries. The methodology adopted for the delineation of anthropogenic impacts is summarised below:

- The specific land use types were derived from the land use map legend therefore, the anthropogenic activities identified with the respective land use zones were categorised into the following:
 - Forestry (existing and felled plantations).
 - Agriculture (commercial sugar cane farming).
 - Mining (current mining and rehabilitated mines or mining areas).
 - Urban and or industrial land use.
 - Rural practises (subsistence land use and farming).
 - Salt water intrusion was not regarded as a land use activity but was rather applicable to operational boreholes situated along or in close proximity to the eastern peripheral study boundary (Indian Ocean).
- Anthropogenic activities per quaternary catchment were identified on the basis that land use comprising >50% of the quaternary catchment was regarded as the primary land use type and land use <50% was assumed to be either secondary or minor.
- Several quaternary catchments straddle the western peripheral boundary of the ZCP (northwestern to southwestern). Therefore, land use and its associated anthropogenic activities are limited to the eight quaternary catchments which are solely encompassed by the study area boundary.

It is important to note that several major surface water bodies and wetlands occur in the study area and therefore represent, in some instances, a major portion of the land use for the respective quaternary catchment. This type of land use is not affiliated with the creation

of anthropogenic activities but is rather considered as potentially being impacted by the surrounding land use and or anthropogenic activities.

Subsequent to the delineation of anthropogenic impacts on the underlying aquifer, case studies and quantitative field investigations extracted from relevant literature sources will be discussed to highlight the severity of such impacts.

4.5 Assumptions and Limitations

The following assumptions are applicable to this dissertation:

- This dissertation is based on available and or existing data which is used throughout the dissertation.
- It is important to note that while the physical extent of the ZCP is c.6,000 km² and incorporates approximately twenty one quaternary catchments, detailed analyses and or calculations are limited to the eight quaternary catchments (W12F, W12J, W13B, W23C, W23D, W32B, W32H and W70A) as these eight catchments are principally underlain by an intergranular or primary aquifer denoted as either the *a3* or *a4* aquifer type. The remaining catchments comprise components of the *a3*, *a4* and *d1* aquifer types, (DWAF, 1998).
- The 'a' type aquifer refers to an intergranular or primary aquifer. The *a3* aquifer is capable of generating borehole yields ranging from 0.5 to 2. L/s while the *a4* aquifer type is higher yielding with borehole yields ranging from 2 to 5 L/s, (DWAF, 1998).
- The *d1* type aquifer is defined as an intergranular and fractured aquifer which is capable of generating borehole yields ranging of 0.1 L/s, (DWAF, 1998).
- In an attempt to substitute the lack of field data, data from the NGA, GRIP and WARMS database were used where deemed necessary. However, one must be cognisant that the GRIP dataset has numerous incomplete borehole records.
- Geological data used for the delineation of hydrostratigraphic units was derived the GRIP and NGA dataset and borehole logs documented in reports from the private sector.
- Where possible, aquifer parameters discussed in Chapter 6-3 were calculated from data recorded on the GRIP database and supplemented where required with quantitative investigations documented by several authors.

The following limitations are applicable to this dissertation:

- The installation of boreholes or monitoring wells, including borehole pump testing to determine aquifer parameters and water quality analyses was outside the proposed scope of work for the dissertation. Due to the unavailability of the aforementioned data, discussions were supplemented by quantitative field investigations documented in

relevant literature sources. The field tasks discussed above represents a major limitation of this dissertation.

- Quantitative hydrogeological and geochemical data is mostly restricted to the Sibayi, Kwabonambi and Uloa Formation's. Hydrogeological and water quality data pertaining to the Kosi Bay and Port Dunford Formation's including the Zululand Group is very limited to negligible.

5 Regional Hydrogeological Characteristics of the Zululand Coastal Aquifers

5.1 Regional Hydrogeology and Groundwater Occurrence

According to the 1: 500 000 scale regional hydrogeological map for Vryheid (DWAF, 1998), the study area is underlain by an intergranular aquifer. The intergranular aquifer is described as water saturated sediments such as sand and gravel where water is stored in the intergranular pores and can be transmitted to boreholes and springs, (Vegter, 2001).

The ZCP aquifer is also regarded as a primary aquifer comprising young (Quaternary Age) unconsolidated sediments. Surficial sands which represent the upper aquifer boundary (*a3* and *a4* aquifer type) form a veneer across the ZCP. The surficial deposits are well rounded, medium grain size sands that are highly permeable and extremely porous, (Maud, 1980).

The regional hydrogeology for the ZCP and its surrounds is illustrated in Figure 5-1. On Figure 5-1, the presence of an intergranular aquifer is denoted by 'a' type aquifers. The spatial distribution of the *a3* type aquifer in Figure 5-1 suggests that the *a3* type aquifer is extensive in comparison to the erratically distributed *a4* type aquifer which has localised occurrence. The *a3* type aquifer produces borehole yields ranging from 0.5 to 2.0 L/s while the *a4* type aquifer is typically higher yielding as boreholes yields ranged between 2.0 to 5.0 L/s, (King, 2003).

The highly permeable nature of the sands allows for the rapid infiltration of precipitation and subsequent recharge to the underlying aquifers. The topography of the coastal plain is flat and therefore the primary aquifer is frequently unconfined in low topographic areas as the shallow groundwater table fluctuates in undulating form and slope, (WRC, 2011).

WRC and DWAF (1995) also confirm that the intergranular aquifer is unconfined and has high hydraulic conductivity and transmissivity properties. Due to the unconfined to shallow groundwater table and hydrogeological properties discussed above, the aquifer is vulnerable to pollution, (Winter *et al.*, 1998).

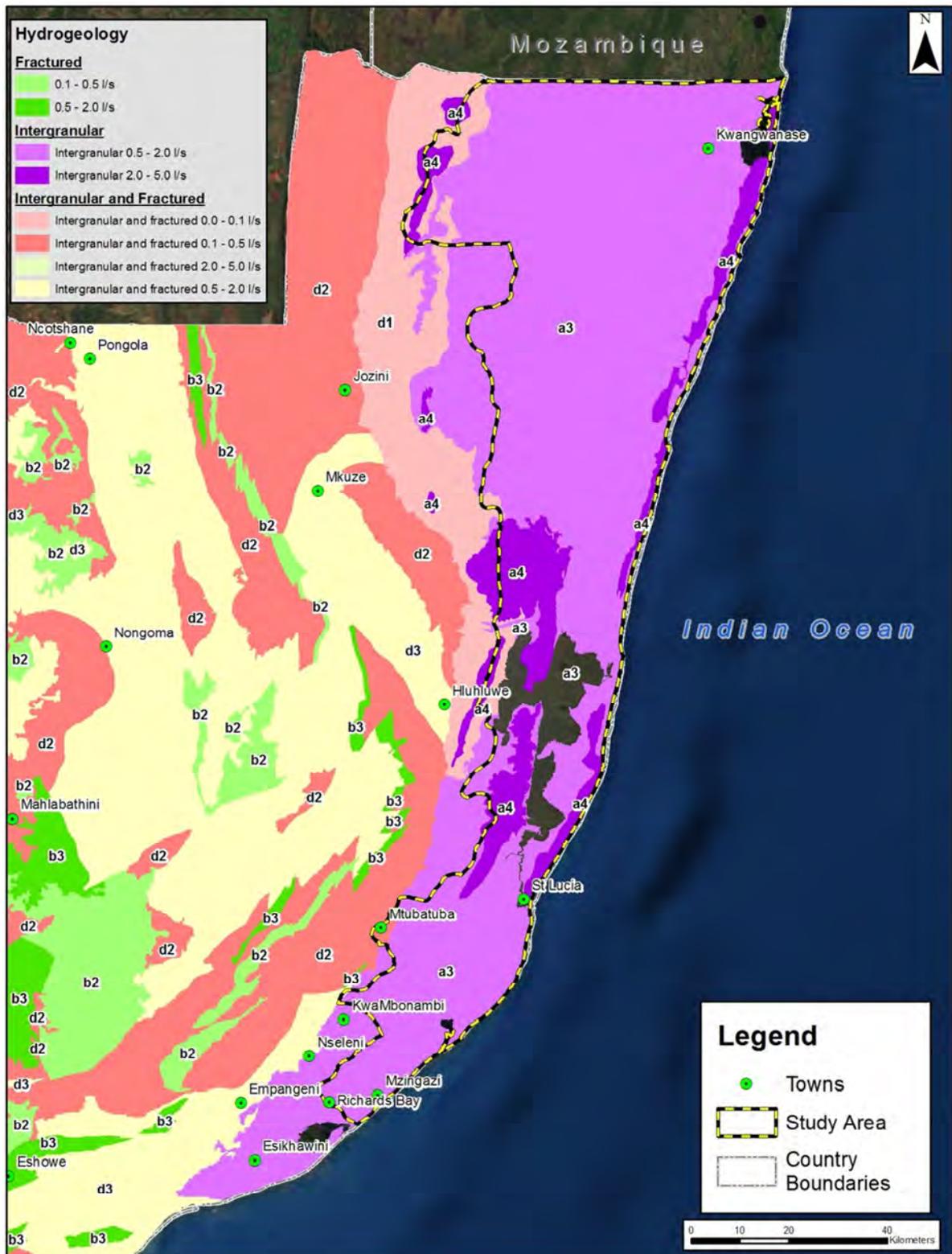


Figure 5-1: Regional Hydrogeological Map for the ZCP, (DWAf, 1998).

Data collected for the NGA and GRIP databases and reports from the private sector was used to formulate a database of 3,248 borehole records. The number of borehole records per quaternary catchment is presented in Table 5-1 and the spatial distribution of the borehole records is shown in Figure 5-2. According to Figure 5-2, the spatial distribution of borehole records is erratically distributed across the study area with quaternary catchments W70A and W32H containing the highest number of borehole records of 1,827 and 284, respectively.

Table 5-1: Borehole Distribution per Quaternary Catchment

Quaternary	Area (km²)	Boreholes	Density (borehole/km²)
W12F	399.00	268	0.67
W12J	332.10	257	0.77
W13B	222.40	257	1.16
W23C	312.60	206	0.66
W23D	247.90	61	0.25
W32B	192.80	88	0.46
W32H	1,275.10	284	0.22
W70A	2,589.00	1,827	0.71
Total	5,570.90	3,248	-

A total of 262 records captured on the Water Authorisation Registration Management System (WARMS) database were reviewed for the Usutu to Mhlatuze WMA. Data analysis of records in the WARMS database for the Umkhanyakhude District Municipality (as the majority of the ZCP falls under this jurisdiction) indicated that only 28 boreholes were registered.

According to the registered groundwater usage in the WARMS database (Table 5-2), water supply services sector utilised the highest volume of water (493,261.2 m³/year) followed by the agricultural sector (184,090 m³/year) where groundwater was utilised for irrigation. However, the volume of groundwater utilised by the water supply sector is expected to be higher on account of Schedule 1 usage which does not require formal registration with the Department of Water Affairs.

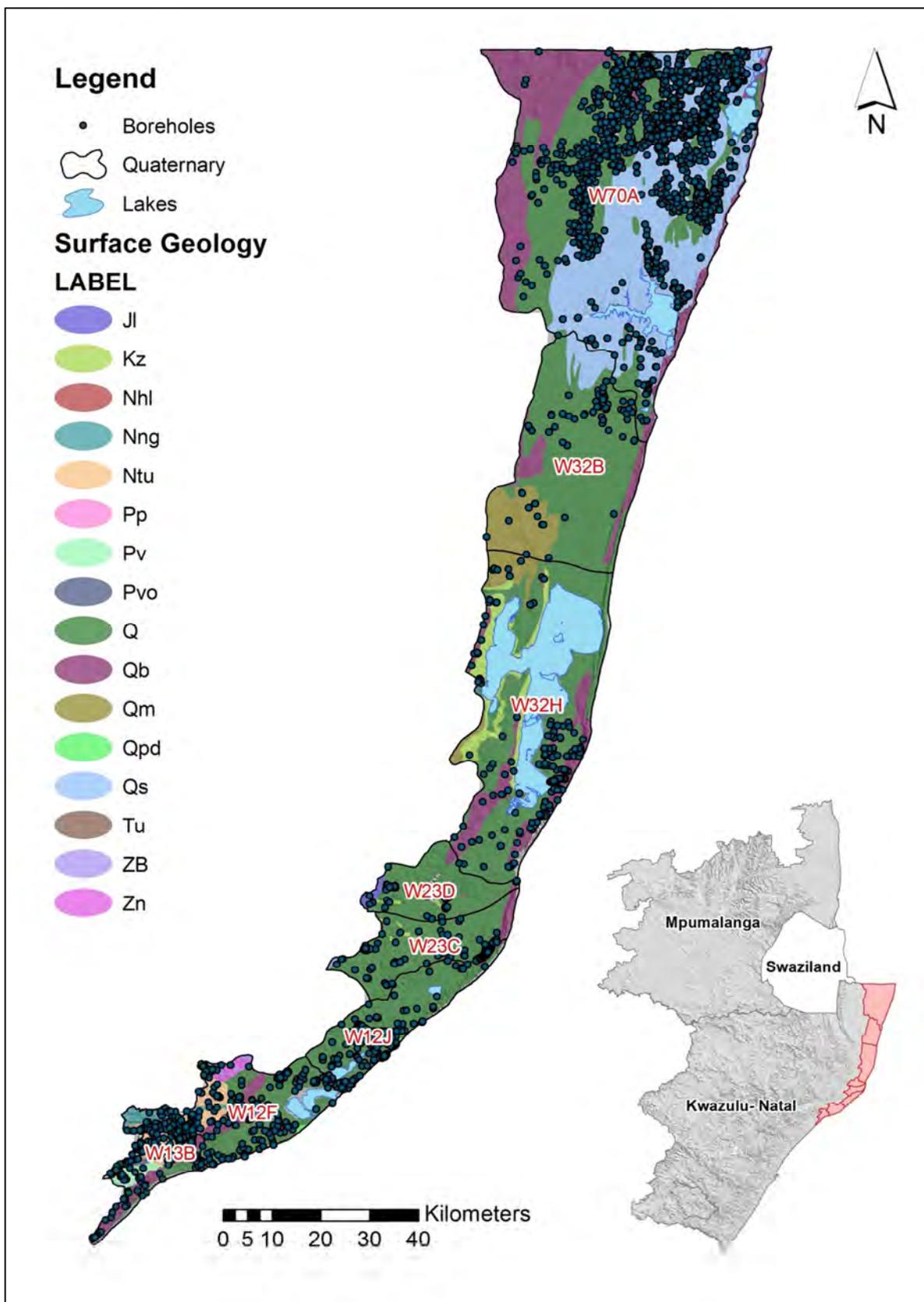


Figure 5-2: Distribution of the Borehole Records In the Eight Quaternary Catchments (W12F, W12J, W13B, W23C, W23D, W32B, W32H, and W70A).

Table 5-2: Registered Groundwater Usage on the WARMS Database for the Umkhanyakhude District Municipality

Quaternary Catchment	Water Use Sector	Groundwater Resource	Registered Volume (m ³ /year)	Total Volume (m ³ /year)
W32H	Water Supply	Boreholes and windmills on government land.	1,0520.4	493,261.2
W32H			2,613.6	
W32H			25,146.0	
W32H			19,920.0	
W32H			16,500.0	
W32H			12,144.0	
W32H			46,068.0	
W32H			79,200.0	
W32H			16,935.6	
W32H			660.0	
W32H			23,865.6	
W32H			78,804.0	
W32H			21,780.0	
W32C			Borehole	
W32C		14,600.0		
W32C		50,000.0		
W32C		14,600.0		
W32C		Schedule 1 Usage	Borehole	
W32G	360.0			
W32F	2,500.0			
W23D	1,500.0			
W31K	Agriculture - Irrigation	Borehole	32,720.0	184,090.0
W32F			11,880.0	
W31K			32,720.0	
W70A			106,250.0	
W23D		Spring	520.0	
W31K	Agriculture - Watering Livestock	Borehole	2,336.0	2,336.0
W32C	Industrial	Borehole	500,00.0	50,000.0
				735,247.2

Data analysed from the Groundwater Resource Assessment (GRA), Phase I database (DWAF, 1995 – 2003) for the W12F, W12J, W13B, W23C, W23D, W32B, W32H and W70A quaternary catchments are tabulated in Table 5-3. According to Table 5-3, the storativity of the weathered zone is significantly higher than that of the fractured zone.

The GRA II assessment (DWAF, 2003 - 2005) examined the hydrogeological properties of the aquifers per quaternary catchment and is shown in Table 5-4. The harvest potential which relates to the annual volume (m^3) of groundwater per km^2 available for exploitation ranged from 10,415,600 $\text{m}^3/\text{a}/\text{catchment}$ (W13B) to 648,489,728 $\text{m}^3/\text{a}/\text{catchment}$ (W70A). This correlates with the exploitability factor (takes into account the aquifer's transmissivity divided by its accessibility) which ranged from 0.4 (W13B) to 0.7 (W70A). The potability factor takes into account groundwater quality issues that may limit development as a domestic supply. All quaternary catchments in the study area had a potability factor of >0.6 which suggests relatively good water quality. However, the values reported in the GRA II database are very conservative and must be treated with caution.

According to the GRA II data tabulated in Table 5-5 which displays the hydrogeological properties of the eight quaternary catchments in the study area under normal and dry or drought conditions, the highest baseflow contribution per annum was recorded in quaternary catchment W70A (63,484,300 $\text{m}^3/\text{a}/\text{catchment}$) while the lowest baseflow contribution of 2,975,500 $\text{m}^3/\text{a}/\text{catchment}$ was reported at W13B. Quaternary catchment W32H reported the highest volume of groundwater abstraction (1,401,310 $\text{m}^3/\text{a}/\text{catchment}$), followed by W13B (451,235 $\text{m}^3/\text{a}/\text{catchment}$) and W12F (131,232 $\text{m}^3/\text{a}/\text{catchment}$).

Quaternary catchment W70A is endowed with significant groundwater resources. This can be observed in both the normal and dry or drought conditions as it recorded the highest utilisable groundwater resource potential (139,450,000 $\text{m}^3/\text{a}/\text{catchment}$ – normal conditions and 89,413,200 $\text{m}^3/\text{a}/\text{catchment}$ – dry or drought conditions) including the highest utilisable potable groundwater exploitation potential (85,270,100 $\text{m}^3/\text{a}/\text{catchment}$ – normal conditions and 54,672,400 $\text{m}^3/\text{a}/\text{catchment}$ – dry or drought conditions). According to DWA (2011), approximately 1×10^6 m^3/a of groundwater use was registered for the Kwangwanase (Manguzi) Water Supply Scheme which is situated in the W70A catchment.

The data presented in Table 5-5 highlights the importance of recharge to the intergranular aquifer as these eight quaternary catchments, which were underlain by either the a3 or a4 type aquifers, showed a significant decrease in groundwater resource potential during periods of drought.

Table 5-3: Aquifer Characteristics for the Quaternary Catchments in the Zululand Coastal Plain – GRA I Database, (DWAF, 1995 – 2003).

Quaternary Catchment	Area (km ²)	Average Water Level (mbgl)	Max. Allowable Water Level Drawdown [median]	Depth (mbgl)		Thickness (m)			Storativity - Volume of Water stored in Aquifer (m ³ /catchment)			5m Drawdown Storage (m ³ /catchment)		Volume	
				Weathered Zone	Fractured Zone	Weathered Zone	Fractured Zone	Aquifer	Weathered Zone	Fractured Zone	Aquifer	Weathered Zone	Fractured Zone		Aquifer
											Sv				
W12F	387	16.54	0	53.63	142.71	36.54	106.16	142.71	17 066 400	3 729 520	20 796 000	2 367 680	0	2 367 680	
W12J	333	14.51	2	47.50	132.50	32.62	99.86	132.50	13 307 200	3 347 890	16 786 900	2 058 470	0	2 058 470	
W13B	223	16.86	0	72.32	173.86	54.13	119.74	173.86	13 524 600	1 651 230	15 175 800	1 258 440	0	1 258 440	
W23C	313	17.21	0	47.50	132.50	29.98	102.52	132.50	11 678 200	3 251 880	14 930 100	1 947 530	0	1 947 530	
W23D	248	14.57	0	47.34	132.18	32.50	99.68	132.18	9 998 530	2 539 820	12 538 400	1 554 590	0	1 554 590	
W32B	934	10.49	0	47.50	132.50	36.83	95.86	132.50	42 443 500	9 122 210	51 934 900	5 842 600	0	5 842 600	
W32H	1 276	22.39	0	47.50	132.50	24.89	107.61	132.50	39 693 900	13 978 100	53 672 100	7 975 030	0	7 975 030	
W70A	2 578	10.07	0	47.50	132.50	37.14	95.36	132.50	116 769 000	24 420 000	141 188 000	15 722 000	0	15 722 000	

Table 5-4: Hydrogeological Properties of the Quaternary Catchments in the Zululand Coastal Plain – GRA II Database, (DWAF, 2003 - 2005).

Quaternary Catchment	Volume of Water stored in Aquifer (m ³)	5m Drawdown Storage Volume (m ³)	Storativity (FZ)	Specific Yield (WZ)	Harvest Potential (m ³ /a/catchment)	Exploitability Factor	Potability Factor
	Sv	Sv _r			HP	Ef	Pf
W12F	20 796 000	2 367 680	0.000092	0.001220	81 289 800	0.500700	0.642860
W12J	16 786 900	2 058 470	0.000100	0.001233	123 853 200	0.692100	1.000000
W13B	15 175 800	1 258 440	0.000064	0.001144	10 415 600	0.400500	0.933330
W23C	14 930 100	1 947 530	0.000100	0.001233	90 651 136	0.593700	0.777780
W23D	12 538 400	1 554 590	0.000104	0.001264	41 317 492	0.503900	0.900000
W32B	51 934 900	5 842 600	0.000100	0.001233	233 257 744	0.693000	0.850000
W32H	53 672 100	7 975 030	0.000100	0.001233	254 448 320	0.574300	0.888890
W70A	141 188 000	15 722 000	0.000100	0.001233	648 489 728	0.700000	0.875000

Table 5-5: Hydrogeological Properties of the Quaternary Catchments in the Zululand Coastal Plain under Normal and Dry or Drought Conditions - GRA II Database, (DWAF, 2003 – 2005).

Quaternary Catchment	Drought Index	Mean Annual Contribution to River Baseflow	Annual Abstraction	Annual Potential Recharge		Groundwater Resource Potential		Groundwater Exploitation Potential		Potable Groundwater Exploitation Potential		Utilisable Groundwater Resource Potential		Utilisable Groundwater Exploitation Potential		Utilisable Potable Groundwater Exploitation Potential	
	years	m ³ /a/catchment		m ³ /a/catchment		m ³ /a/catchment		m ³ /a/catchment		m ³ /a/catchment		m ³ /a/catchment		m ³ /a/catchment		m ³ /a/catchment	
				Normal	Dry	Normal	Dry	Normal	Dry	Normal	Dry	Normal	Dry	Normal	Dry	Normal	Dry
	Di	Bf	At	Re	Re (dry)	AGRP	AGRP (dry)	GEP	GEP (dry)	PGEP	PGEP (dry)	UGRP	UGRP (dry)	UGEP	UGEP (dry)	UPGEP	UPGEP (dry)
W12F	4.78	14 050 800	131 232	53 372 700	43 149 200	37 763 700	28 699 000	18 683 900	13 926 900	12 011 100	8 953 050	37 621 300	28 612 500	18 475 500	13 791 200	11 914 000	8 896 240
W12J	10.28	11 957 500	0	46 585 400	36 251 200	32 626 800	23 794 700	22 700 600	16 549 700	22 700 600	16 549 700	33 513 400	24 328 200	23 207 100	16 832 300	23 059 600	16 748 100
W13B	1.00	2 975 500	451 235	31 003 100	25 261 400	26 031 600	20 992 400	10 259 500	8 206 930	9 575 480	7 659 770	25 512 400	20 362 800	10 133 400	8 028 260	9 373 620	7 423 490
W23C	7.57	11 062 100	0	37 459 700	30 636 000	26 129 600	19 509 400	15 703 100	11 779 200	12 213 600	9 161 610	26 813 000	20 063 400	15 897 200	11 957 600	12 421 700	9 345 500
W23D	6.33	8 694 730	50 200	26 323 800	21 130 700	17 974 800	12 930 800	9 207 360	6 710 830	8 286 620	6 039 750	17 961 500	12 851 400	9 100 740	6 592 290	8 103 820	5 867 720
W32B	15.59	28 093 100	3 103	89 215 900	69 733 000	61 005 000	41 845 600	42 385 400	29 091 700	36 027 600	24 727 900	61 092 100	41 837 900	42 306 200	28 984 700	35 833 500	24 549 800
W32H	9.71	41 671 200	1 401 310	113 788 000	88 039 000	71 127 400	47 028 200	40 965 400	27 291 500	36 413 700	24 259 100	70 607 400	46 107 300	40 297 000	26 503 000	35 646 600	23 428 200
W70A	16.03	63 484 300	38 760	205 550 000	152 619 000	138 682 000	89 246 400	97 077 700	62 472 500	84 943 000	54 663 400	139 450 000	89 413 200	97 615 200	62 589 200	85 270 100	54 672 400

5.2 Recharge

Recharge is a complex process and the volume of rainfall that enters the groundwater system is a function of the rate and volume of rainfall, soil type, antecedent moisture, geology and topography. For comparative and estimative purposes, recharge is represented as a percentage of Mean Annual Precipitation (% MAP). However, one must be mindful of gross simplification of a complex process, (Parsons, 2004).

Rainfall is the principal recharge mechanism for the primary aquifers in the ZCP, (Kelbe and Germishuys, 2001) and the highly permeable nature of the sands promotes rapid recharge to the intergranular aquifer, (WRC, 2011). However, recharge via seepage from several pans, lakes and shallow peat swamps represents minimal contribution to groundwater, (Parsons, 2004).

The analyses of groundwater samples collected in the vicinity of Lake Sibaya displayed an isotopically depleted signature which was similar to that of rainfall samples analysed in the vicinity of Lake Sibaya. The study suggested that the depleted isotopic signature was indicative of direct recharge from rainfall without undergoing any evaporation, (Weitz and Demlie, 2013).

Rawlins (1991) study along the Eastern Shores of Lake St. Lucia highlighted the close relationship between shallow groundwater and surface processes. Analyses of several hydrographs suggested that the groundwater levels correlated well with periods of rainfall. However, the magnitude of groundwater response was influenced by the overlying vegetation type.

The influence of vegetation on recharge was demonstrated by the investigations undertaken by Rawlins and Kelbe (1992) in the Richards Bay area. The study revealed that a response in the groundwater table in areas vegetated by natural grassland where the groundwater table was estimated at c.2 to 3 mbgl, would only be detected if a rainfall event exceeded 10 mm.

Meyer *et al.*, (2001) calculated recharge values for the study area using chloride deposition rates and the volume of rainfall measured per annum. Based on the above, effective recharge as a percentage of MAP was at 18% along the coast which diminished to 5% at 50 km inland.

Rainfall exhibits a prominent east-west gradient and decreases from 1,200 mm/a along the coast to <600 mm/a inland and then increases to 700 mm/a in the vicinity of the Lebombo Mountains, (Pitman and Hutchinson, 1975). Quaternary catchments W12F, W12J, W13B and W70A generally have a MAP of >1, 000 mm/a while rainfall gauge W4E004 situated in

Makatini Flats (c.11 km east of the Lebombo Mountains, W45A² quaternary catchment) has a MAP of 789 mm/a (Figure 5-3). The MAP data for the rainfall gauges in the aforementioned quaternary catchments are presented in Appendix 1, (<http://www.dwa.gov.za/hydrology>) and confirms the prominent east-west MAP gradient.

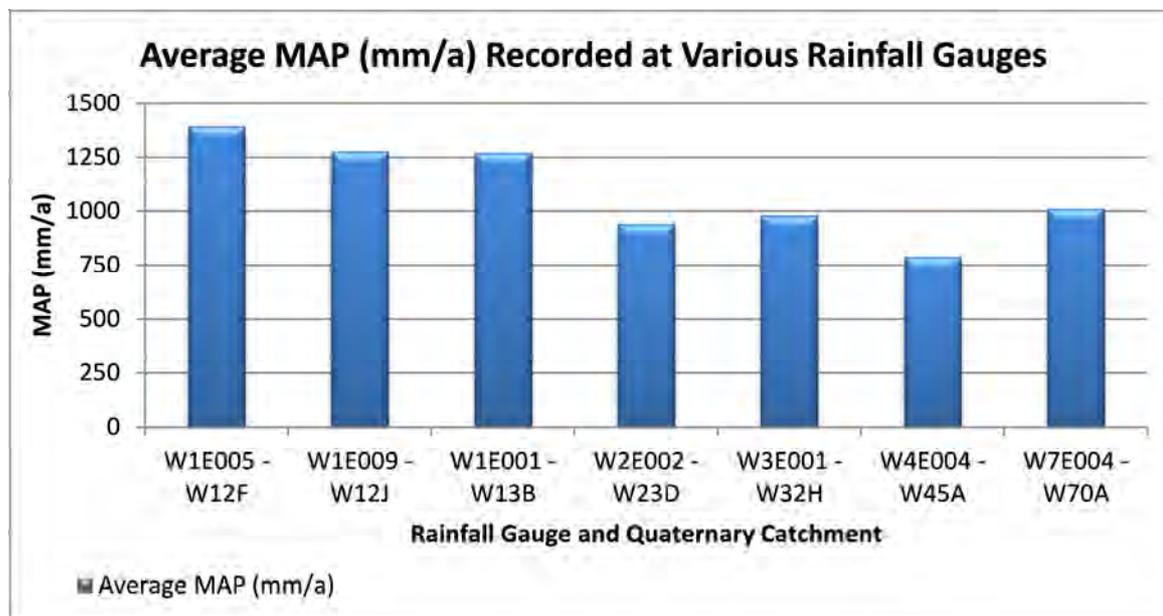


Figure 5-3: Mean Annual Precipitation Graph for Rainfall Gauges Distributed across the ZCP, (<http://www.dwa.gov.za/hydrology>).

The MAP derived from the GRIP database and the Water Resources of South Africa (WRC, 2005) which is commonly referred to as WR2005, including the Mean Annual Runoff (MAR) for the Zululand Coastal Plain are comparable and are presented in Table 5-6. Recharge values as a percentage of MAP which is collated from several literatures sources are tabulated in Table 5-7.

Table 5-6: Mean Annual Precipitation (MAP) and Mean Annual Runoff (MAR) for the Quaternary Catchments in the ZCP (mm/a), (GRIP Database; WRC, 2005).

Quaternary Catchment	Area (km ²)	MAP - GRIP Data	MAP - WR2005, (WRC, 2005)	Mean Runoff (GRIP Data)	Annual (mm/a)
W12F	399	1,285.33	1,285		270.1
W12J	332.1	1,280.10	1,280		248
W13B	222.4	1,293.09	1,293		351.3
W23C	312.6	1,136.25	1,136		178.8
W23D	247.9	1,038.58	1,039		138.8
W32B	192.8	900.66	901		74.5

² Quaternary catchment W45A is only included for comparison purposes and is excluded from the list of eight quaternary catchments which this dissertation focuses on.

Quaternary Catchment	Area (km ²)	MAP - GRIP Data	MAP - WR2005, (WRC, 2005)	Mean Runoff (GRIP Data)	Annual (mm/a)
W32H	1,275.1	957.99	958		97.1
W70A	2589	768.88	769		42.9
Average		873.1	873		103.7

Table 5-7: Recharge for the Zululand Coastal Aquifer as a Percentage of MAP (cited from literature).

Reference	Recharge as a Percent (%) of Mean Annual Precipitation (MAP)
Worthington (1978)	24
Campbell <i>et al.</i> , (1992)	8 – 30
Meyer <i>et al.</i> , (2001)	5 – 18
Parsons (2004) ³	20 – 30
Cobbing <i>et al.</i> , (2008)	5 – 18

5.3 Groundwater Levels

Parsons (2004) stated that groundwater moves from areas of higher hydraulic pressures to areas of lower pressure in the direction of the hydraulic gradient. According to discussions in Section 3-2, the topography of the ZCP is characterised by the steeply sloping Lebombo Mountain (651 mamsl) which gently flattens at the eastern foothills giving rise to the extensive ZCP (15 to 20 mamsl), (Porat and Botha, 2008). However, the relatively flat topography across the ZCP (Figure 3-3) displays an abrupt increase in the surface relief closer to the coast due to the presence of the coastal barrier dune cordons along the coastline, (Sudan *et al.*, 2004).

In an attempt to collect water level data, Worthington (1978) undertook 420 well point observations around Lake Mzingazi and areas accessible around the Mhlatuze River. The dataset was further supplemented by water levels measured in the boreholes drilled as part of the investigation. It is important to note the findings of Worthington (1978) investigation which serve as a representation of baseline groundwater conditions in the study area. Interpretation of the piezometric surfaces from Worthington's (1978) study revealed the following:

- Most areas displayed significant vertical hydraulic conductivity throughout the permeable succession therefore the water level was related to the entire permeable succession.

³ Parsons (2004) referred to recharge of sandy – alluvial aquifers and not direct reference to the ZCP aquifer.

- The presence of clay or silty sand at shallow depths in certain areas, created a perched to semi-perched groundwater table.
- The shallow water levels recorded in the boreholes drilled was a reflection of the piezometric head in the deeper layers as the boreholes penetrated the water bearing Uloa Formation.

Groundwater levels in the 180 mamsl coastal barrier dune complex were at 20 mamsl, (Cobbing *et al.*, 2008). The groundwater gradient towards the coast is steep (1:50 – 1:100) and induces fresh water seeps along the coast, (Meyer *et al.*, 2001).

Geostatistical analysis of water level data collated from NGA, GRIP and private sector reports is presented in Chapter 6-1.3 and is therefore representative of relatively recent data. The analysis of water strikes is discussed in Chapter 6-1.6.

5.4 Groundwater Hydraulics

Kelbe and Germishuyse (2010) examined the flow dynamics of homogenous systems and reported that vertical flow processes are the dominant flow mechanism in unsaturated media, with lateral flow typically occurring when the porous media is close to saturation and the flow is generally slower.

Using the data recorded on the GRIP database, a correlation coefficient of 0.975 (water levels versus topography) was calculated for the boreholes which contained water level data (Figure 5-4). The calculated correlation coefficient confirms that a strong Bayesian relationship exists in the study area as groundwater levels mimicked topography. As groundwater levels follow topography which is relatively flat across the ZCP, it can be assumed that groundwater flow occurs under unconfined to semi-confined conditions.

A Bayesian relationship was also evident for the wells registered on the GRIP database (Figure 5-5), with a higher correlation coefficient of 0.995.

Using water levels data from the GRIP and NGA database and reports from the private sector, the groundwater flow direction for the study area was contoured using the Bayesian Interpolation Technique and is shown in Figure 5-6. According to Figure 5-6, the study area is characterised by moderate to shallow water levels (<50 mamsl) which become very shallow (0 to 30 mamsl) in close proximity to the coast. The regional groundwater flow direction which is assumed to be topographically controlled is therefore inferred towards the east, in the direction of the Indian Ocean. However, one must be cognisant that localised flow towards wetlands and surface water bodies in the study area is expected to occur on account of local heterogeneities in the aquifer and that groundwater flow in the coastal dunes is unlikely to be influenced by topography.

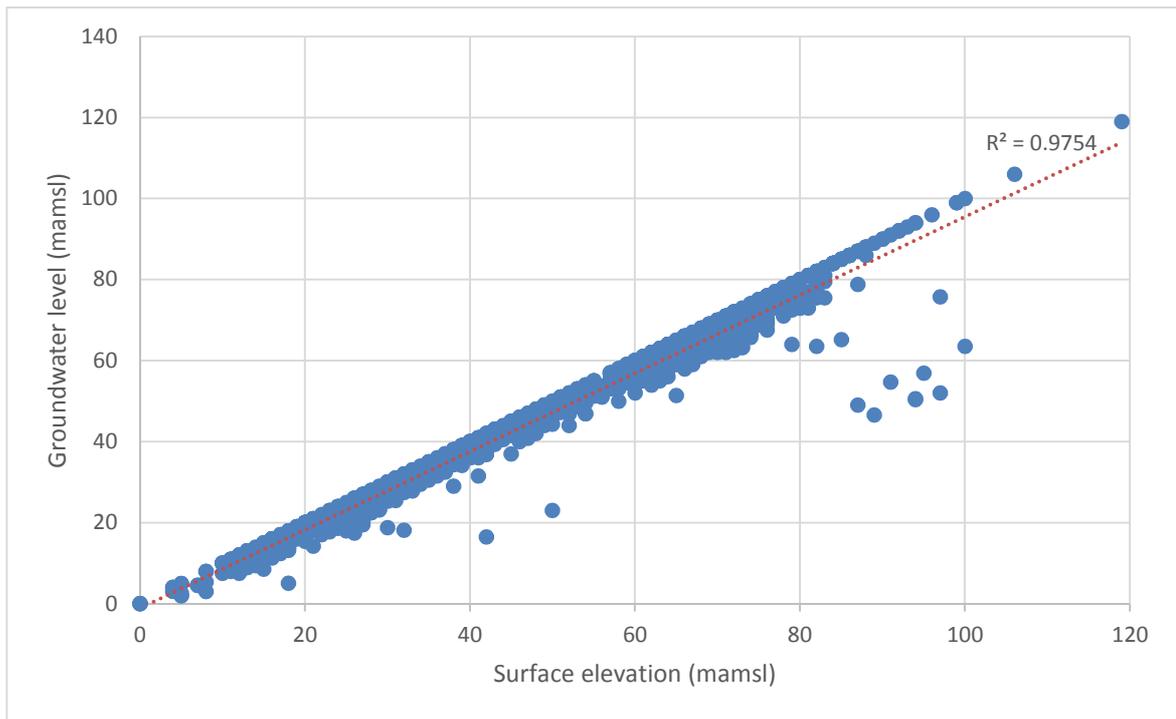


Figure 5-4: Surface Elevation vs Groundwater Elevation for Boreholes Recorded on the GRIP Database.

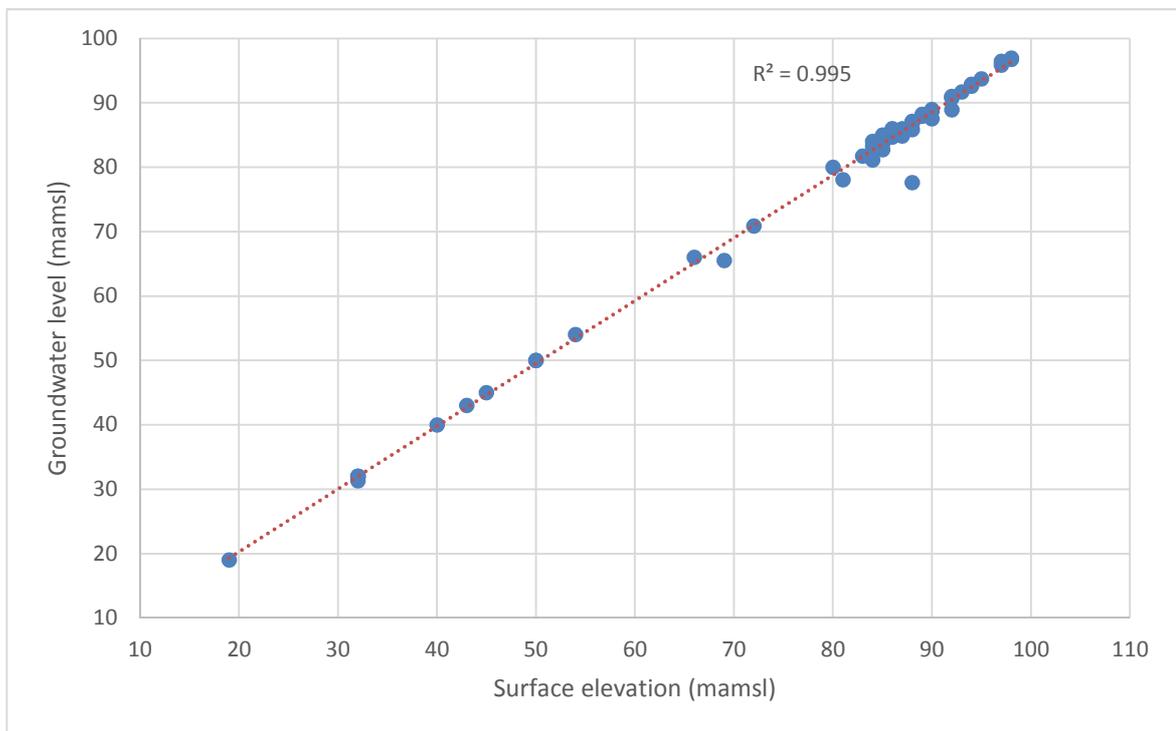


Figure 5-5: Surface Elevation vs Groundwater Elevation for Wells Recorded on the GRIP Database.

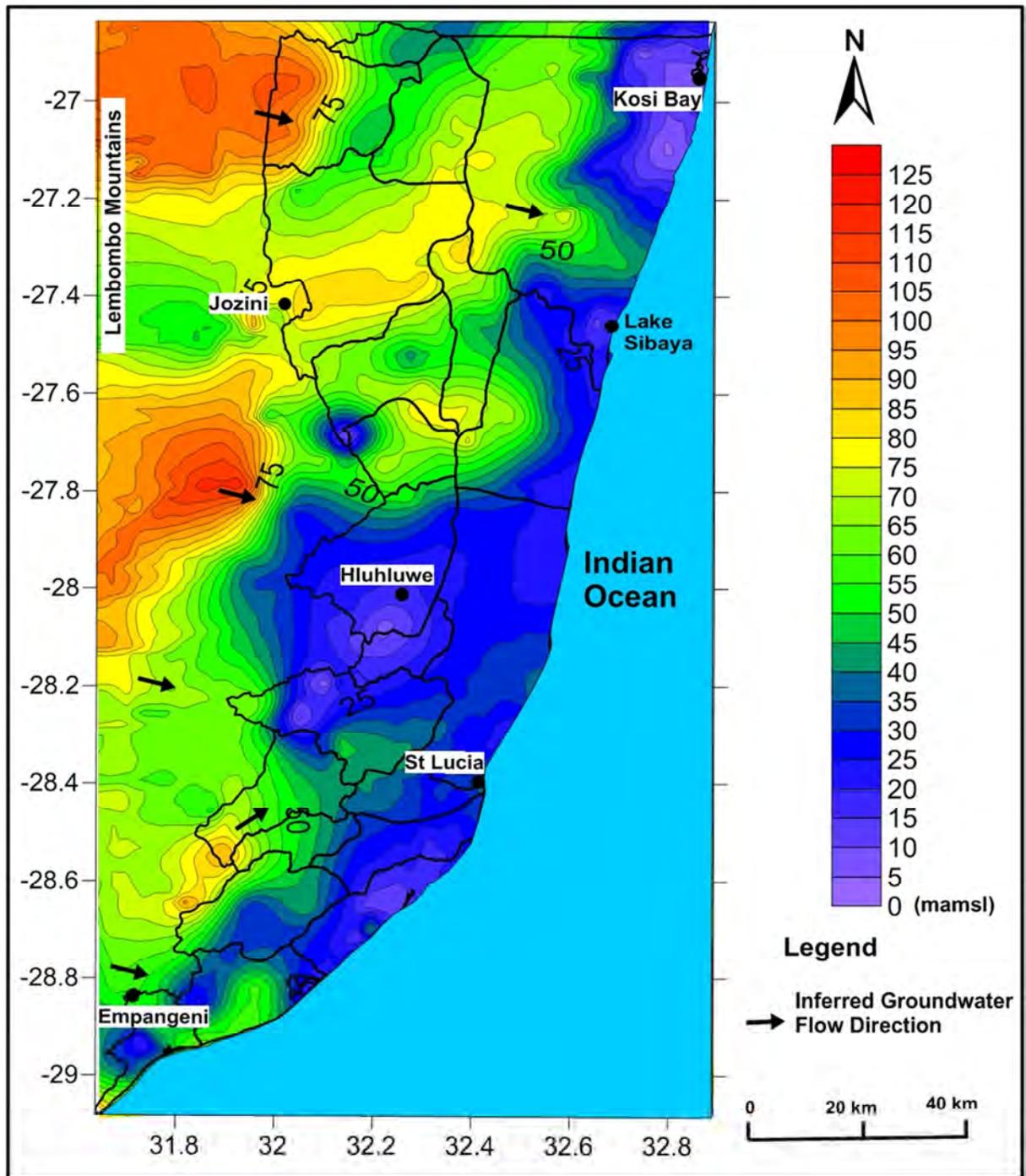


Figure 5-6: Bayesian Interpolation Map Showing the Groundwater Level (mamsl) for the Zululand Coastal Plain, (GRIP and NGA Database and Water Levels Derived from the Private Sector Reports).

6 Delineation of the Groundwater Region 65 – Zululand Coastal Aquifer

6.1 Introduction

The methodology adopted for the delineation of hydrostratigraphic units for the Zululand Coastal Aquifer (ZCA) is discussed in detail in Chapter 4-2 and 4-3. Vegter's (2001) methodology was predominantly used. However certain geostatistical analyses as prescribed by Vegter (2001) could not be undertaken on account of incomplete datasets.

6.1.1 Simplified Geology

It is evident from the regional geology discussed in Section 3-7, that the geology for the ZCP is complex. Therefore to correlate the geology recorded in the borehole logs with the regional geology for the ZCP, the geology for the eight quaternary catchments was simplified and is shown in Table 6-1 and shown in Figure 6-1.

Table 6-1: Simplified Geology

Acronym	Lithostratigraphic Unit	Dominant Lithology	Subordinate Lithologies
Q	Quaternary Age	Alluvium, sand, calcrete.	Arenite.
Qpd	Deposits	Sand and arenite.	Mudstone and lignite.
Qb	Bluff Formation	Alluvium, sand, calcrete.	-
Qm	Masotcheni Formation	Sand.	-
Qs	Salnova Formation	Arenite.	-
Tu	Uloa Formation	Calcarenite and conglomerate.	Limestone.
Kz	Zululand Group	Siltstone and conglomerate.	Arenite.
Jl	Lebombo Group	Basalt and rhyolite.	-
Nhl	Hlobane Complex	Olivine gabbro.	Gabbro.
Nng	Nigramoep Formation	Gneiss.	-
Ntu	Tuma Formation	Amphibolite.	Gneiss and schist.
Pv	Vryheid Formation	Sandstone, mudstone, shale and dolerite.	Coal and siltstone.
Pvo	Volksrust Formation		
ZB	Unnamed potassic granite and gneiss	Granite.	-
Zn	Nondweni Formation	-	Amphibolite.

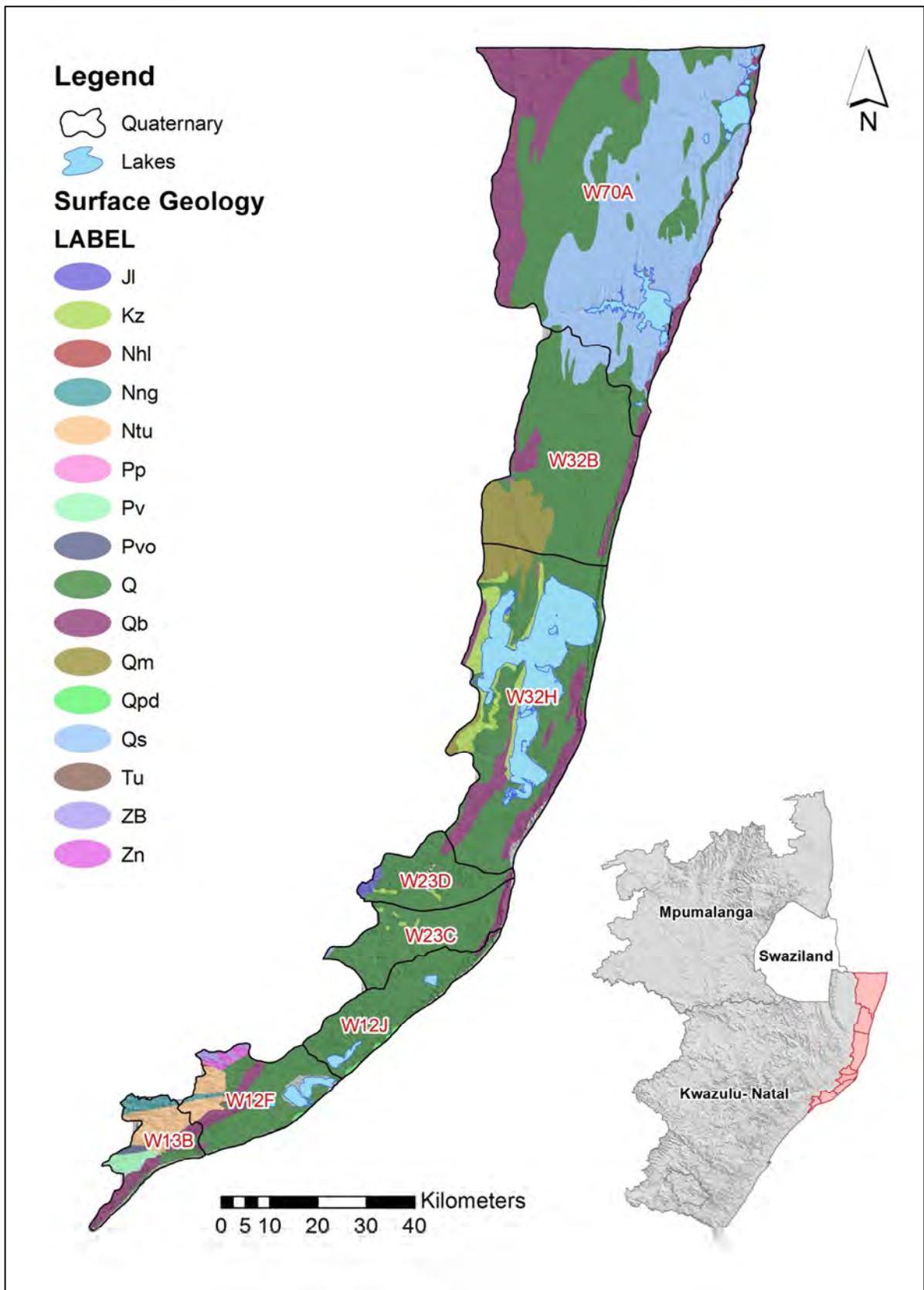


Figure 6-1: Simplified Geological Map for Quaternary Catchments W70A, W32B, W32H, W23D, W23C, W12J, W12F and W13B

6.1.2 Borehole Distribution

The distribution of borehole records across the ZCP is erratic, as displayed in Figure 5-2. This suggests that selected areas were targeted for investigations of hydrogeological significance hence the irregular spatial borehole distribution. A summary of the borehole densities intercepting the simplified geological formations discussed in Chapter 6-1.1 is tabulated in Table 6-2 and assumes a uniform borehole distribution over the ZCP.

According to Table 6-2, boreholes were predominantly installed in the Quaternary Age deposits comprising the Q (1,513 boreholes) and Qs (1,095) lithostratigraphic units' which is extensive across the ZCP. The least number of boreholes (0.5 boreholes/km²) was installed in the Hlobane Complex and Uloa Formation. It is important to note that the literature review (Section 2) indicates that the Uloa Formation is regarded as a very productive aquifer, (Worthington, 1978; Meyer *et al.*, 2001; Cobbing *et al.*, 2008) and the limited number of boreholes installed in the Uloa Formation can possibly be attributed to both its erratic and limited distribution.

Table 6-2: Borehole Distribution in the Simplified Geological Formations (NGA and GRIP Database).

Acronym	Lithostratigraphic Unit	Area (km ²)	Borehole Records	Density (boreholes/km ²)
Q	Quaternary Age Deposits	3,016.8	1,513	0.5
Qpd		7.1	31	4.35
Qb	Bluff Formation	796.1	315	0.4
Qm	Masotcheni Formation	214.5	27	0.13
Qs	Salnova Formation	1,174.7	1,095	0.93
Tu	Uloa Formation	3.9	2	0.51
Kz	Zululand Group	134.3	21	0.16
Jl	Lebombo Group	12.2	8	0.65
Nhl	Hlobane Complex	0.7	2	2.90
Nng	Nigramoep Formation	30.3	21	0.69
Ntu	Tuma Formation	116.8	141	1.21
Pv	Pietermaritzburg Formation	27.8	35	1.26
Pvo	Vryheid Formation	7.0	14	2.00
ZB	Unnamed potassic granite and gneiss	11.6	8	0.69
Zn	Nondweni Formation	17.0	15	0.88
Total		5,570.9	3,248	

6.1.3 Water Level Analysis

Water level data in relation to surface topography (Bayesian relationship) was analysed in an attempt to understand groundwater hydraulics in the different lithologies. Thereafter, the boreholes were categorised according to the respective depths which allowed for the identification of several systems. Geostatistical analyses of the water level data derived from the NGA and GRIP dataset including borehole logs from reports published by the private sector for the simplified geological formations (Section 6-1.1) in the ZCP are presented below.

Q – Quaternary Age Water Levels

The Q dataset comprises 782 borehole records. A total of four systems were identified (Figure 6-2) and each system displayed a good Bayesian correlation (Figure 6-3). The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 6-4.

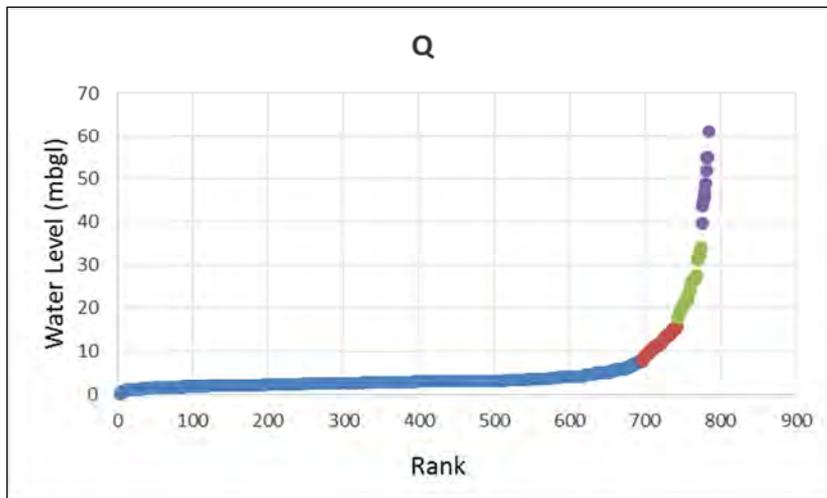


Figure 6-2: Q – Quaternary Age Deposits, Groundwater Level vs Rank

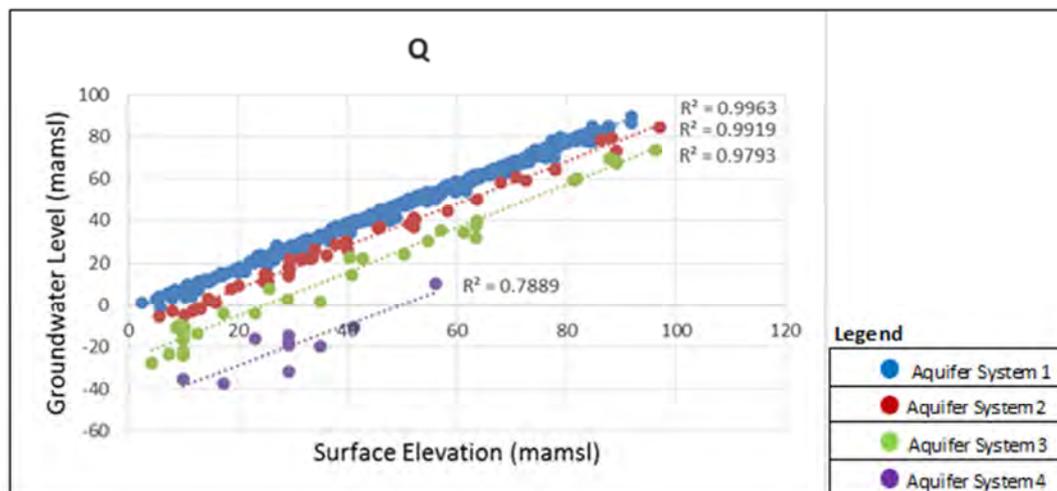


Figure 6-3: Q – Quaternary Age Deposits, Groundwater Level vs Surface Elevation

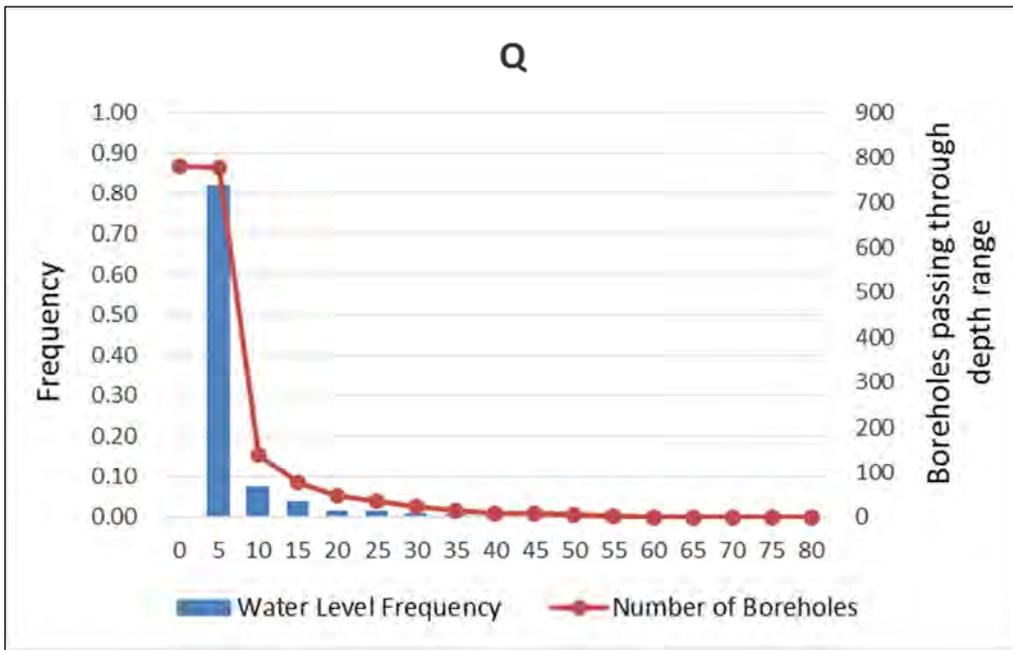


Figure 6-4: Q – Quaternary Age Deposits, Groundwater Level Distribution.

Qb – Bluff Formation Water Levels

A total of 92 borehole records were available for the Qb dataset. Analyses of the data indicated that two systems were present (Figure 6-5) with each displaying good correlation between surface topography and water levels (Figure 6-6). The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 6-7.

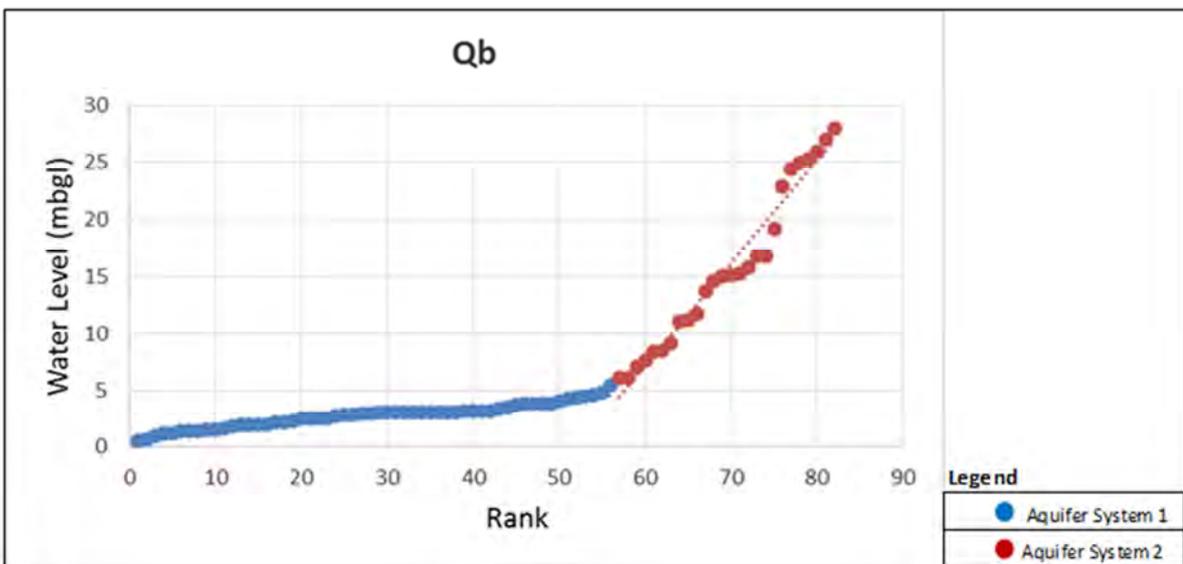


Figure 6-5: Qb – Bluff Formation, Groundwater Level vs Rank

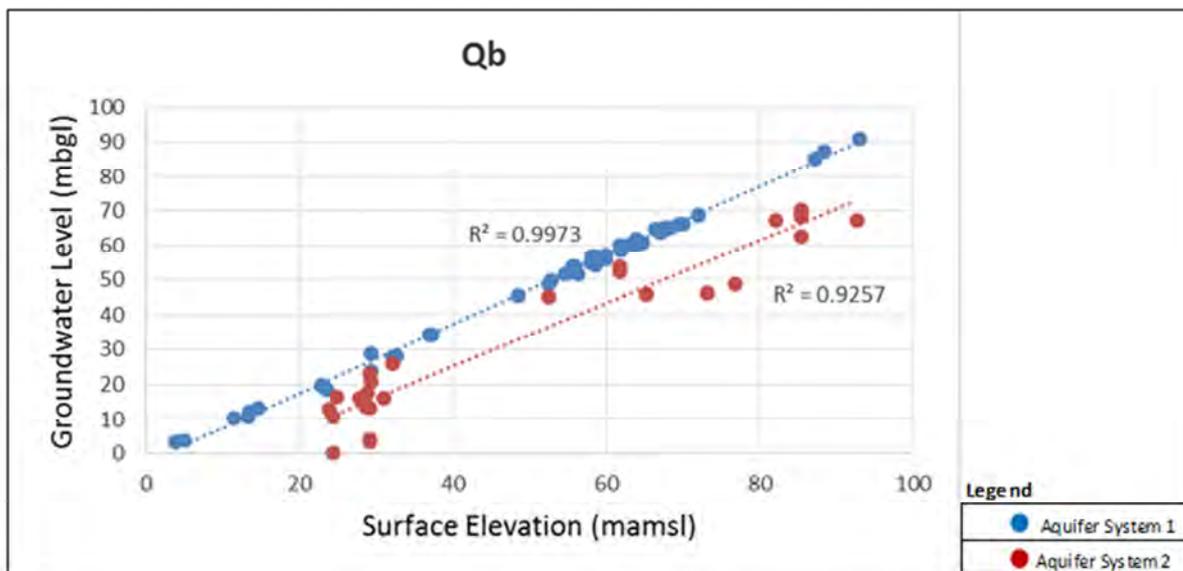


Figure 6-6: Qb – Bluff Formation, Groundwater Level vs Topography

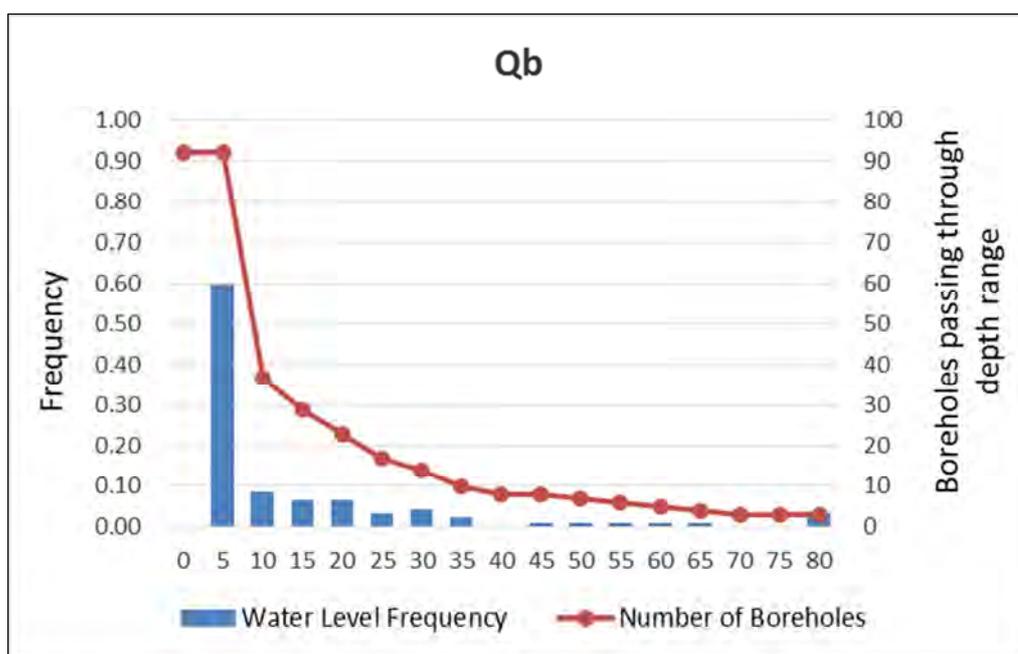


Figure 6-7: Qb – Bluff Formation, Distribution of Groundwater Levels

Qm – Masotcheni Formation Water Levels

Analyses of 17 borehole records indicated that two systems were also evident (Figure 6-8) with each system displaying a high correlation between water level and surface topography (Figure 6-9). The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 6-10.

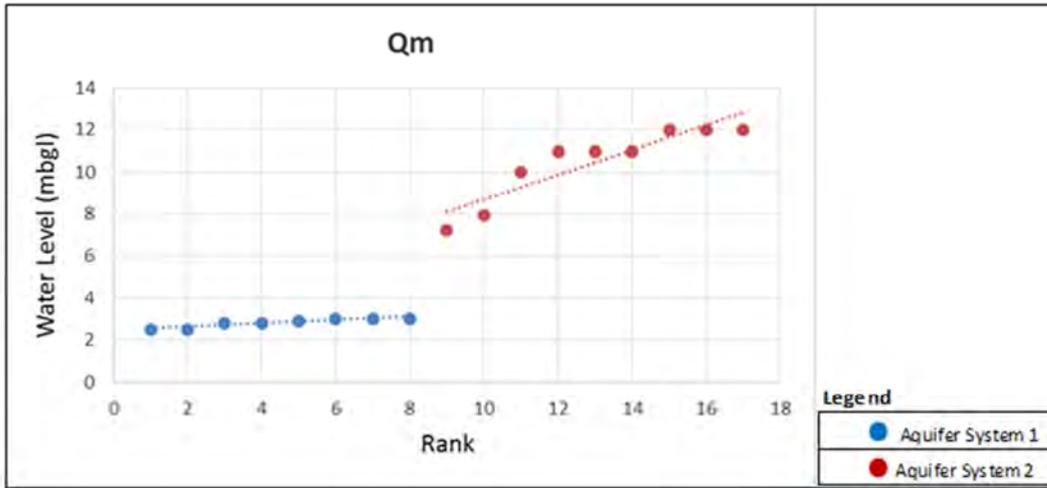


Figure 6-8: Qm – Masotcheni Formation, Groundwater Level vs Rank

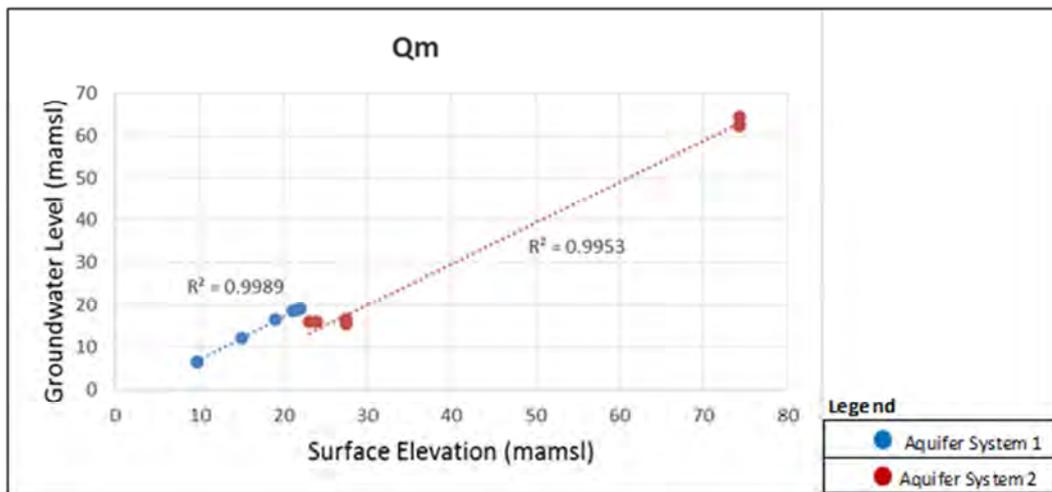


Figure 6-9: Qm – Masotcheni Formation, Groundwater Level vs Topography

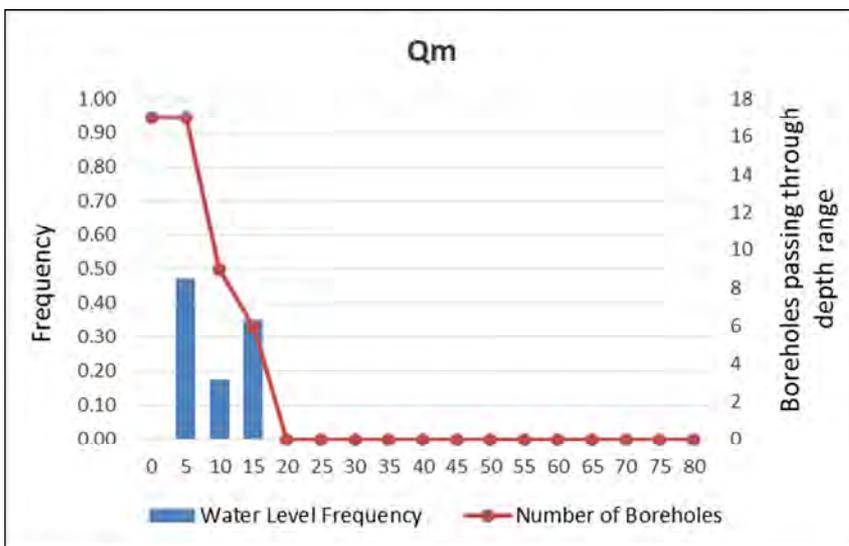


Figure 6-10: Qm – Masotcheni Formation, Groundwater Level Distribution

Qs - Salnova Formation Water Levels

The Qs dataset comprised 959 borehole records which showed the occurrence of two systems (Figure 6-11) with each displaying a high correlation between water level and topography (Figure 6-12). The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 6-13.

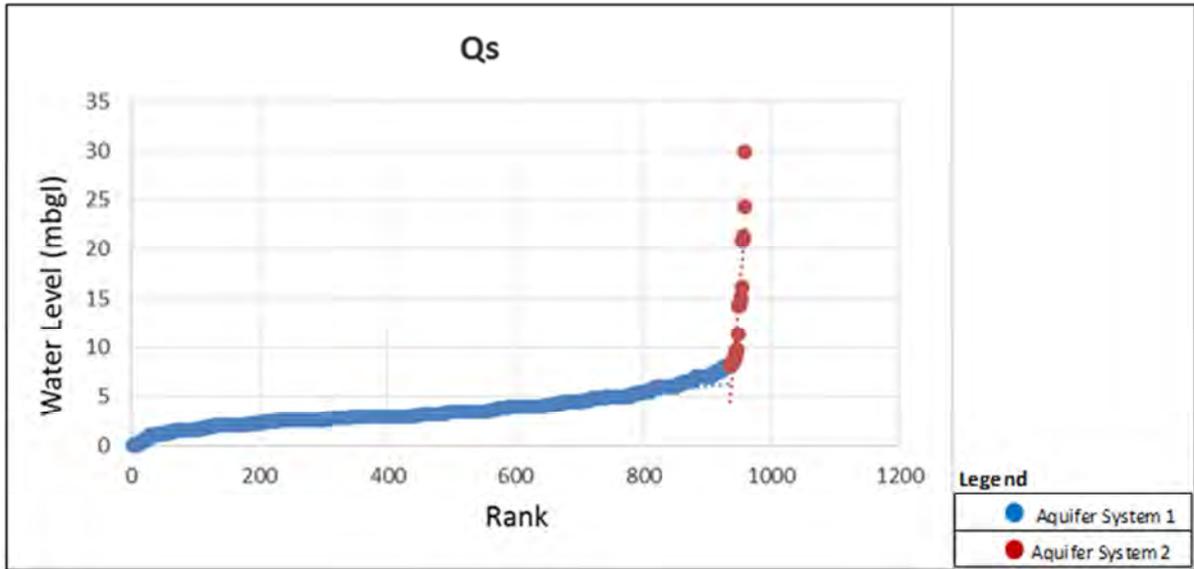


Figure 6-11: Qs – Salnova Formation, Groundwater Level vs Rank

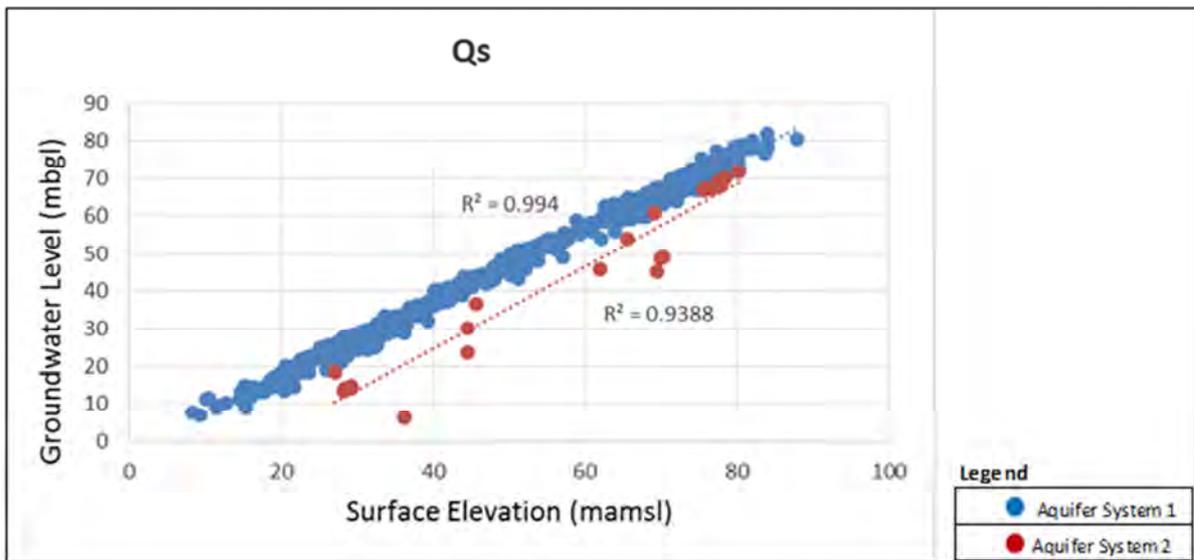


Figure 6-12: Qs – Salnova Formation, Groundwater Elevation vs Topography

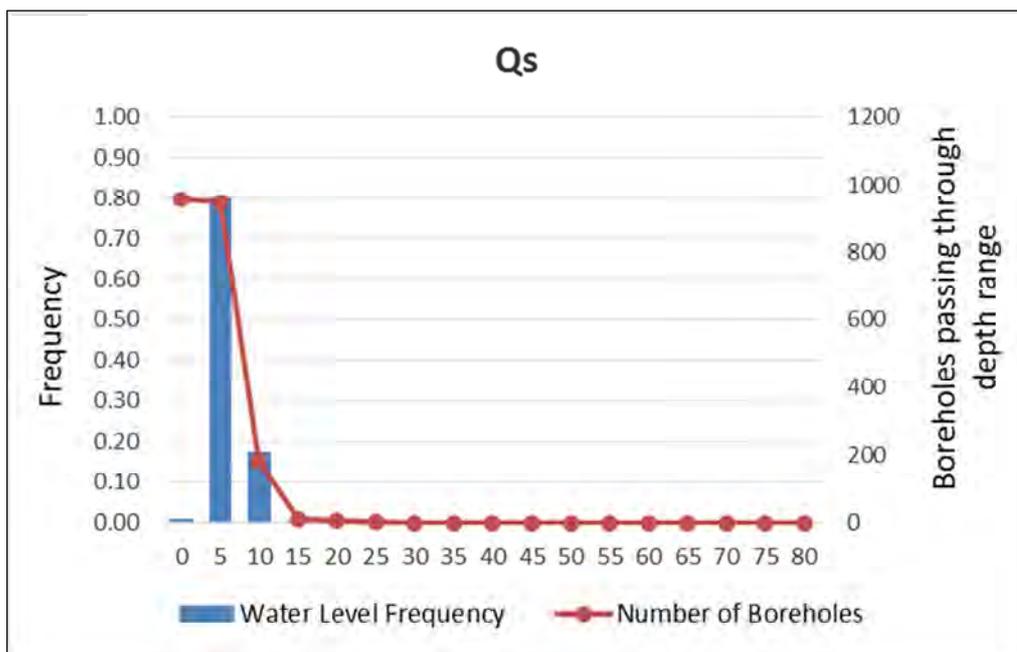


Figure 6-13: Qs – Salnova Formation, Groundwater Level Distribution.

Kz – Zululand Group Water Levels

The Kz dataset had only two water level records (Figure 6-14) therefore the Bayesian relationship could not be examined.

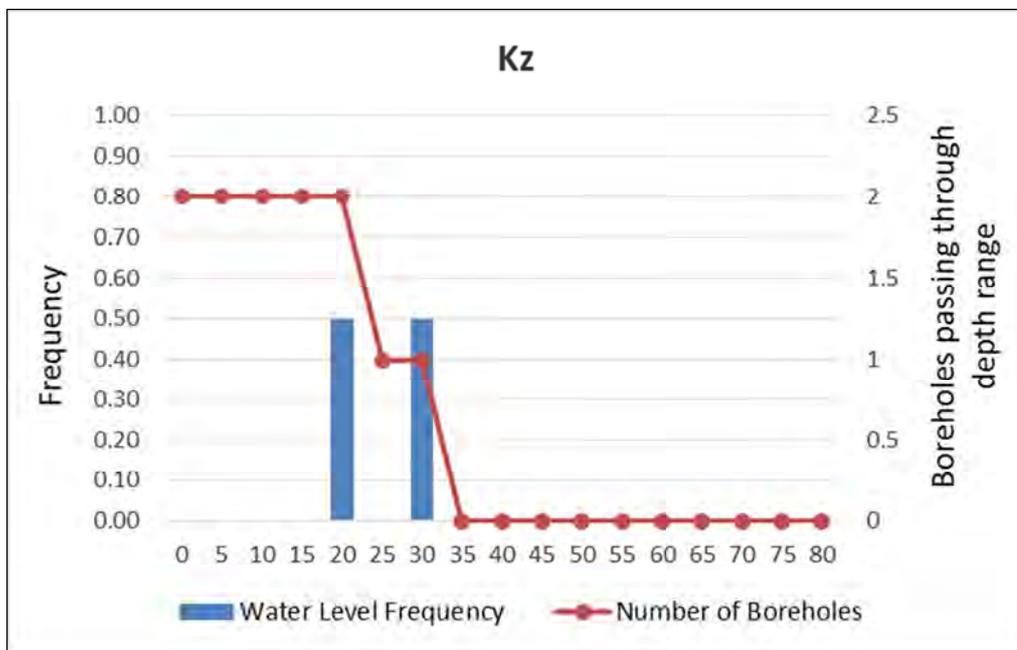


Figure 6-14: Kz - Zululand Group, Groundwater Level Frequency per Depth

Ntu – Tuma Formation Water Levels

The Tuma Formation (Ntu) dataset comprised a total of 17 boreholes where two different systems were identified (Figure 6-15) and each system exhibited a high correlation between water level and topography (Figure 6-16). The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 6-17.

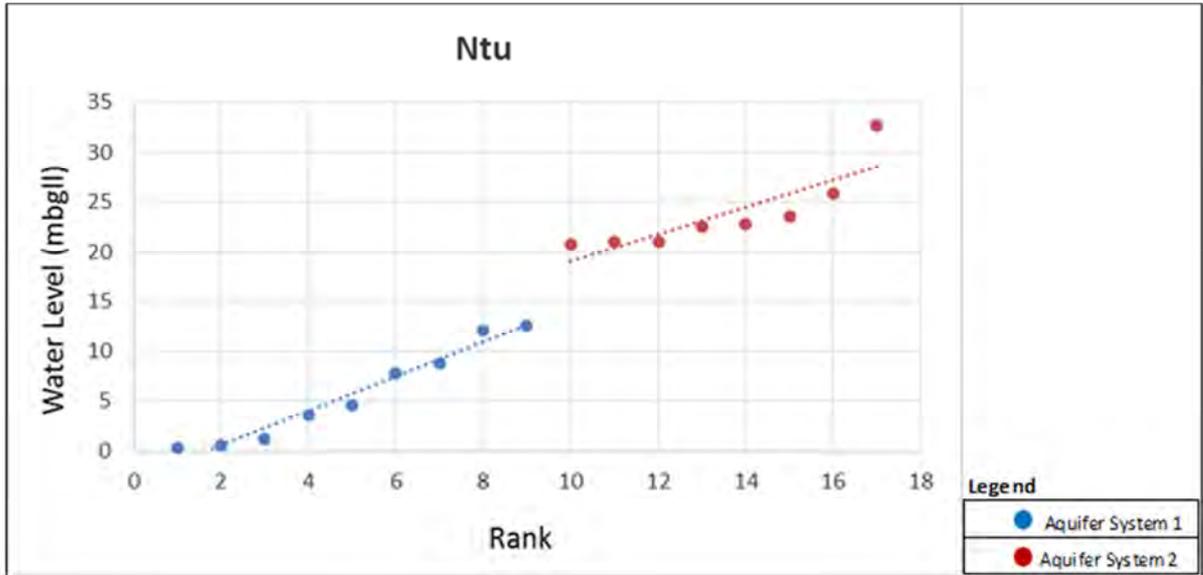


Figure 6-15: Ntu – Tuma Formation, Groundwater Level vs Rank.

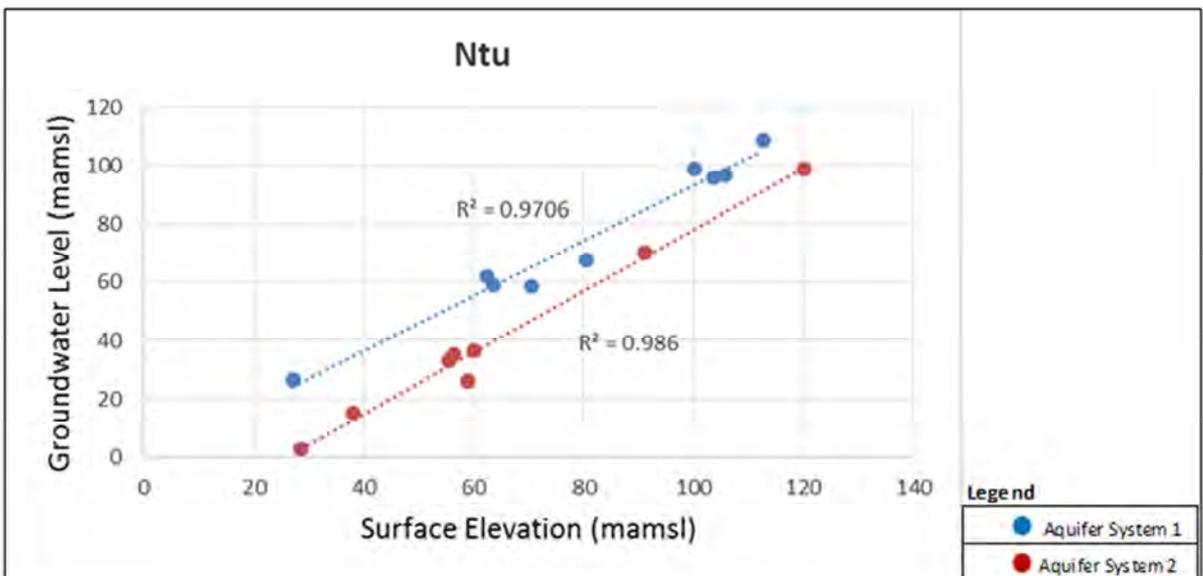


Figure 6-16: Ntu – Tuma Formation, Groundwater Level vs Topography.

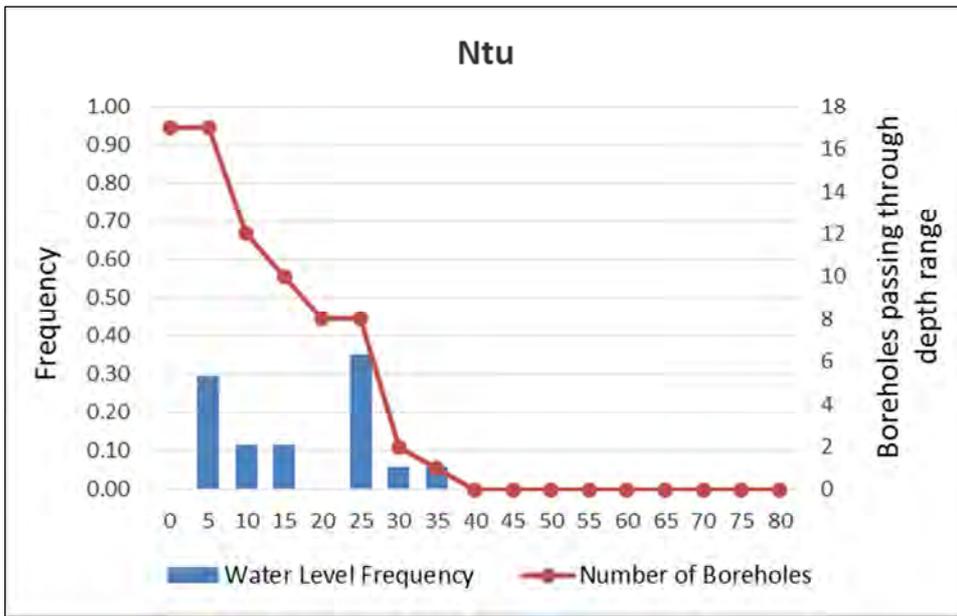


Figure 6-17: Ntu, Tuma Formation, Groundwater Level Distribution.

Pv – Vryheid Formation Water Levels

The Ntu comprise a total number of 22 boreholes and two different systems are identified which is shown in Figure 6-18. A very high correlation is displayed by the system representing the shallow aquifer in comparison to the deeper system which has a lower Bayesian correlation (Figure 6-19). The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 6-20.

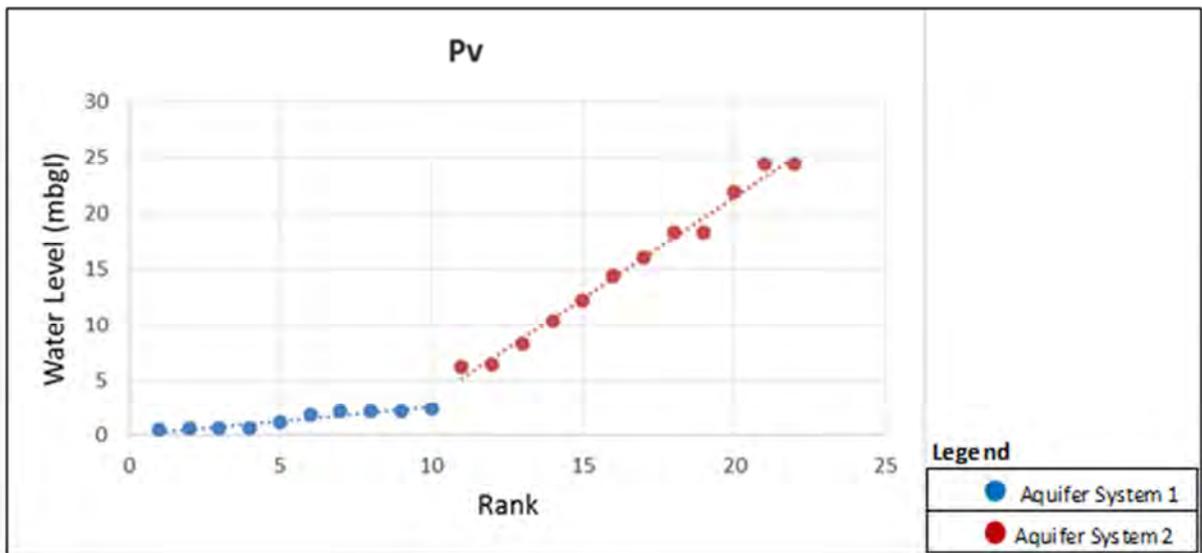


Figure 6-18: Pv - Vryheid Formation, Groundwater Level vs Rank.

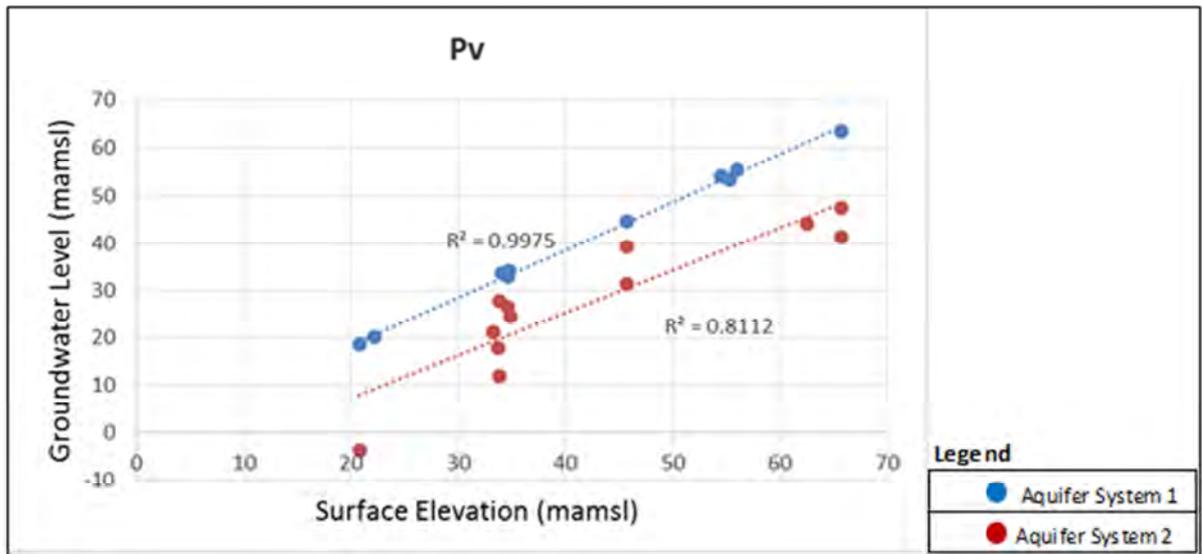


Figure 6-19: Pv, Vryheid Formation, Groundwater Level vs Topography

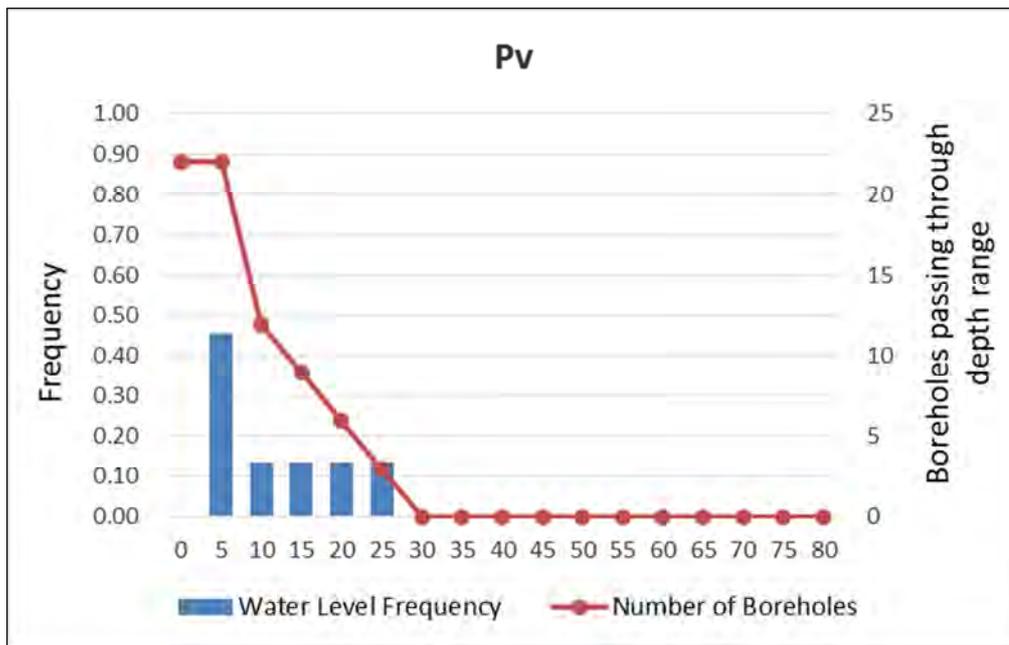


Figure 6-20: Pv, Vryheid Formation Groundwater Level Distribution.

Pvo – Volksrust Formation Water Levels

The Pvo comprise a total number of 5 boreholes and only one system was identified as shown in Figure 6-21. This aquifer displays a good Bayesian correlation (Figure 6-22).

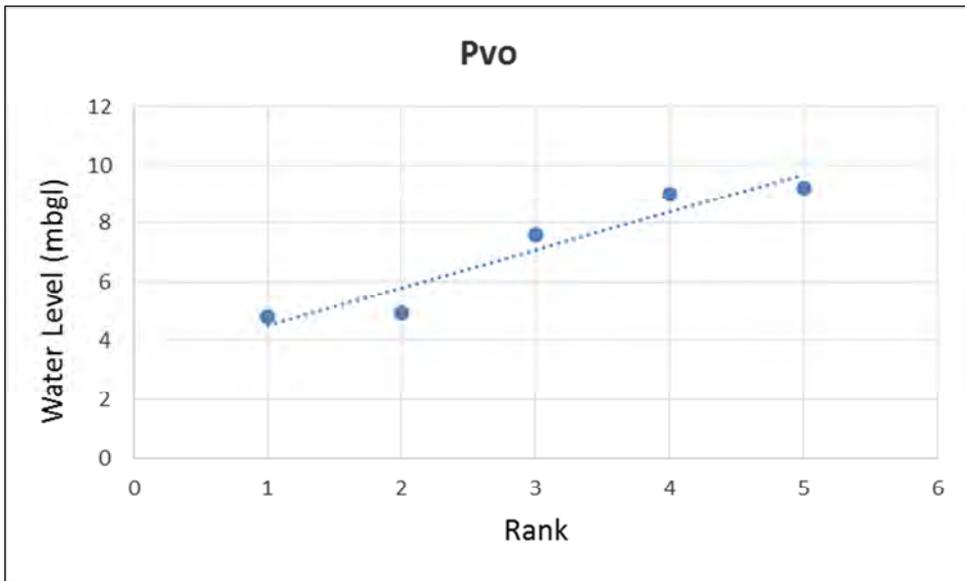


Figure 6-21: Pvo, Volksrust Formation, Groundwater Level vs Rank.

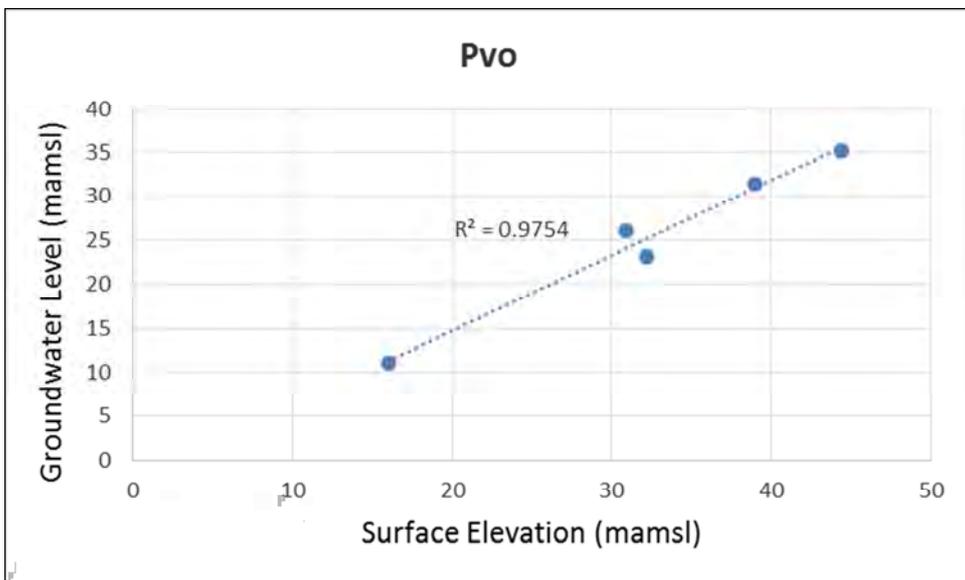


Figure 6-22: Pvo, Volksrust Formation, Groundwater Levels vs Topography

Zn – Nondweni Formation Water Levels

The Zn dataset comprises eight boreholes and only one system was identified. This is shown in Figure 6-23. There is a very poor correlation (Figure 6-24) between the groundwater level and topography which is likely to be attributed to a few boreholes that are situated in close proximity to each other. The distribution of groundwater levels per depth and the number of boreholes passing through the depth range is shown in Figure 6-25.

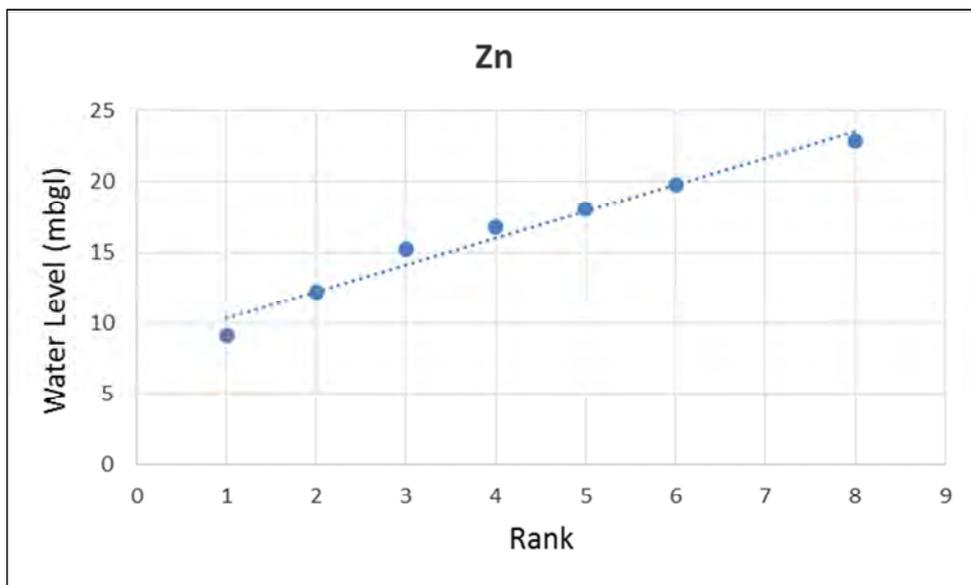


Figure 6-23: Zn - Nondweni Group, Groundwater Level vs Rank.

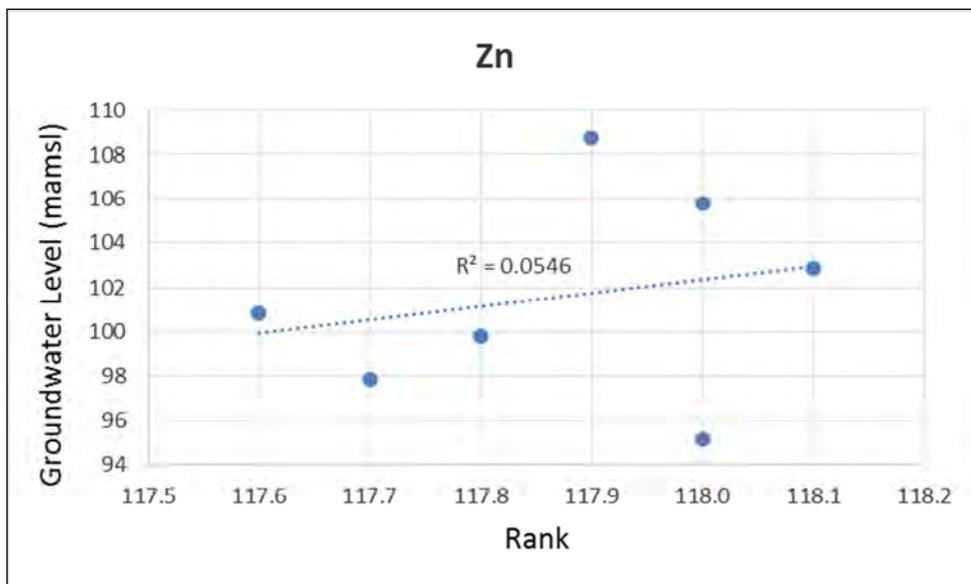


Figure 6-24: Zn – Nondweni Group, Groundwater Level vs Topography.

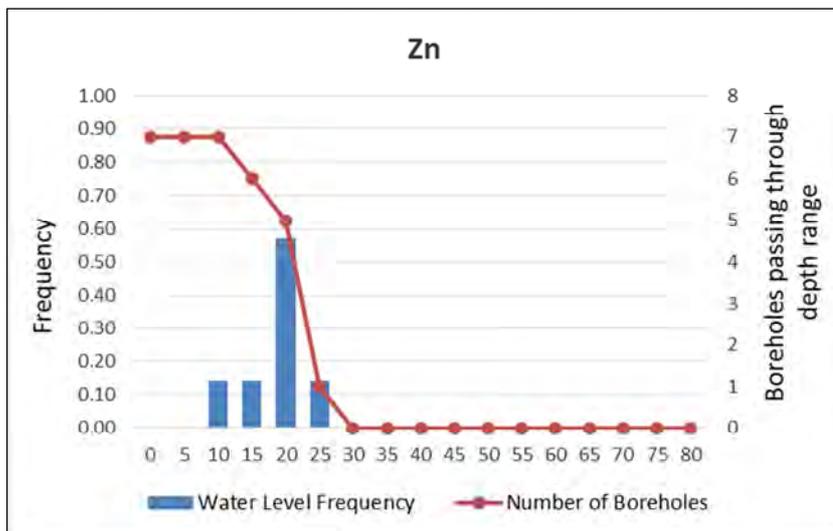


Figure 6-25: Zn – Nondweni Group, Groundwater Level Distribution

6.1.4 Borehole Depths

A summary of the average borehole depths and elevations of the respective geological formations is presented in Table 6-3 and shown in Figure 6-26.

Table 6-3: Summary of Average Borehole Depths and Elevations

Geology	Area (%)	Borehole Depth (mbgl)			Elevation (mamsl)		
		Average	Std. Dev. ⁴	Count	Average	Std. Dev.	Count
Q	54.2	22.0	33.0	807	50.1	36.0	1,513
Qb	14.3	37.3	37.1	103	51.9	26.4	315
Qm	3.9	19.4	11.3	21	33.9	21.9	27
Qs	21.1	7.8	6.9	940	51.9	21.1	1,095
Kz	2.4	47.7	37.5	13	41.0	16.0	21
Ntu	2.1	73.3	38.3	23	85.2	34.9	141
Pv	0.5	41.5	14.1	28	46.9	15.8	35
Pvo	0.1	39.0	23.8	10	29.4	8.3	14
Zn	0.3	56.9	30.5	14	119.6	14.3	15
		Total		1,959	Total		3,176

⁴ Std Dev. in Table 6-3 and 6-4 refers to standard deviation.

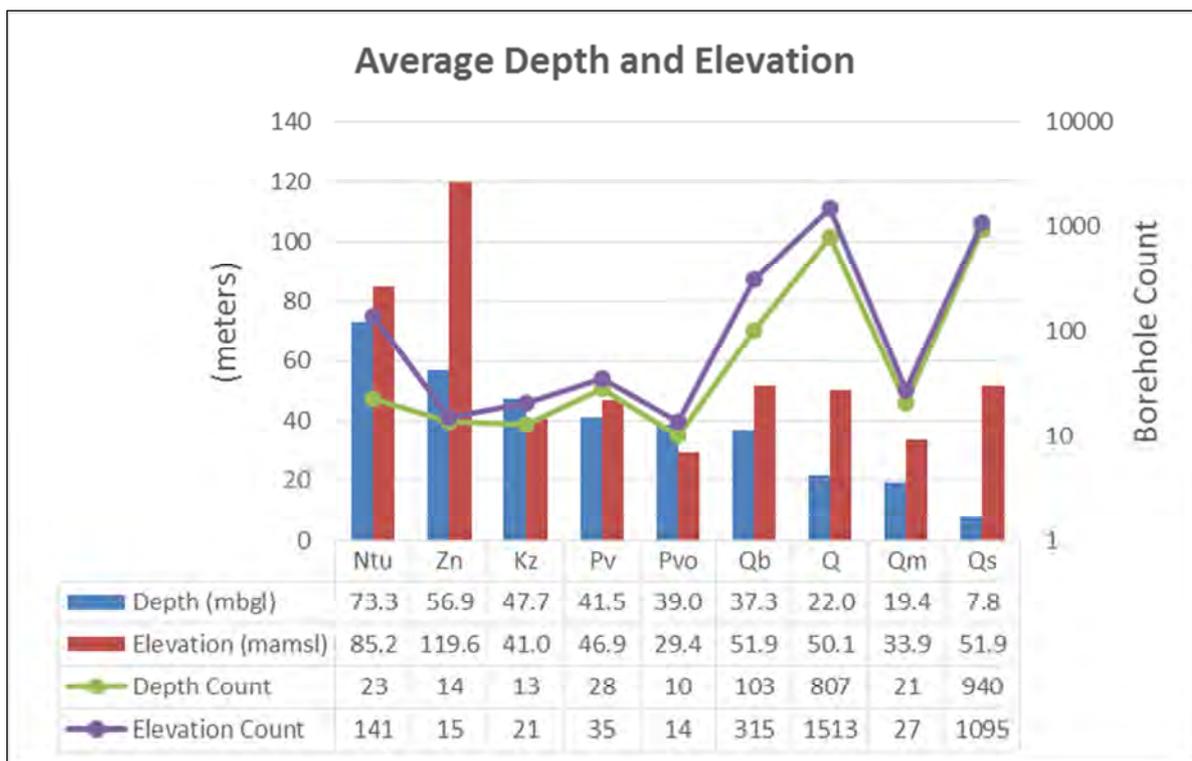


Figure 6-26: Average Borehole Depth and Elevation

6.1.5 Borehole Yields

The average borehole yields for the simplified geology discussed in Chapter 6-1.1 are presented in Table 6-4. The borehole yield refers to the yield measured at the end of drilling while the discharge refers to the discharge rate measured from an equipped borehole.

Table 6-4: Summary of Average Borehole Yield and Discharge (L/s)

Geology	Area (%)	Borehole Yield (L/s)			Borehole Discharge (L/s)		
		Average	Std. Dev.	Count	Average	Std. Dev.	Count
Q	54.20	16.91	10.18	696	1.69	2.87	81
Qb	14.30	11.46	10.76	75	0.77	1.43	28
Qm	3.90	7.35	8.40	16	1.47	1.25	7
Qs	21.10	18.92	7.69	937	5.92	6.82	3
Kz	2.40	0.02	0.04	6	0.10	-	1
Ntu	2.10	0.60	0.90	12	0.52	0.56	17
Pv	0.50	2.21	1.41	24	1.80	1.70	4
Pvo	0.10	1.85	1.45	5	0.42	0.22	6
Zn	0.30	1.64	3.19	9	1.83	3.35	8

According to Table 6-4, it is evident that the Quaternary sands are generally high yielding and productive aquifers however one should be cognisant that the high yield values

reported can possibly be attributed to the significant numbers of boreholes intercepting the geological formation, for example the 'Q' related formations. Graphical representation of the data tabulated above is shown in Figure 6-27.

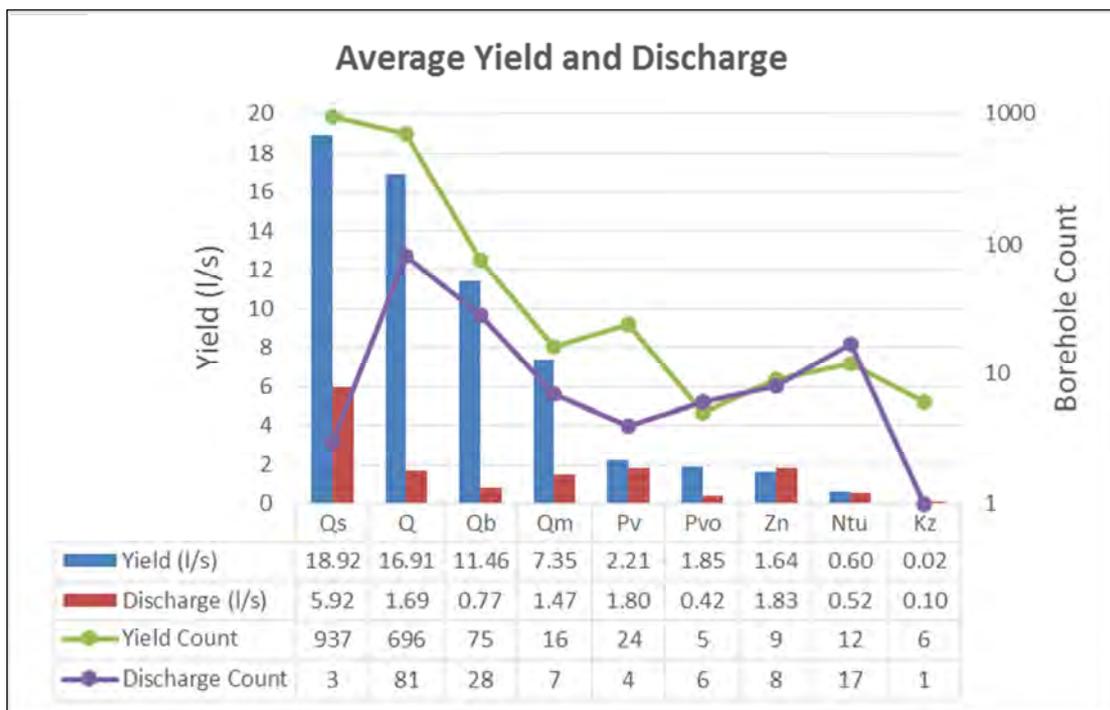


Figure 6-27: Average Borehole Yield and Discharge (L/s).

6.1.6 Water Strikes

Analysis of the water strikes and yields were undertaken on borehole records which had both strike and borehole depth information and are shown in Figure 6-28. Based on Figure 6-28, it is evident that the Quaternary Deposits (Q, Qb, Qm and Qs) are the most productive aquifers in comparison to the remaining lithologies which are generally <2 L/s. High yielding strikes which typically occur in Q, Qb, Qm and Qs, generally occur at <15 mbgl and are in the magnitude of 0 to 22 L/s with the majority of yield measurements exceeding 3 L/s.

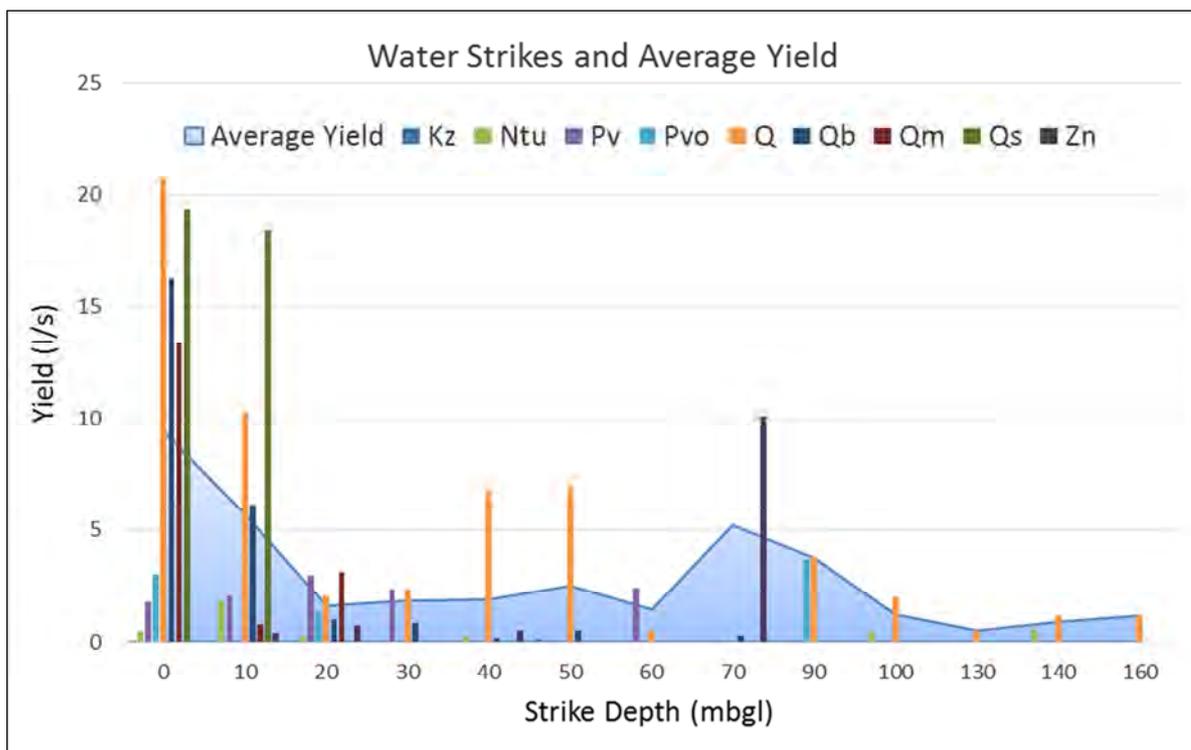


Figure 6-28: Average Water Strike Depth (mbgl) and Yield (L/s)

The strike frequency⁵ for each lithostratigraphic unit was calculated to assess trends associated with the strike depths and the number of boreholes passing through the depth range. Thereafter, the cumulative strike frequency was calculated per lithology and is defined as the sum of all preceding strike frequencies per depth. The strike frequency for the respective lithologies as defined in Section 6-1.1 is presented below:

Q – Quaternary Age Strike Frequency

The strike frequency for Q was calculated using 807 borehole records which contained strike information. According to Figure 6-29, the dominant strike frequency occurs at 10 mbgl followed by 170 to 180 mbgl.

⁵ Strike frequency = $\frac{\text{No. of strikes per depth range below surface}}{\text{Number of boreholes passing through the depth range}}$

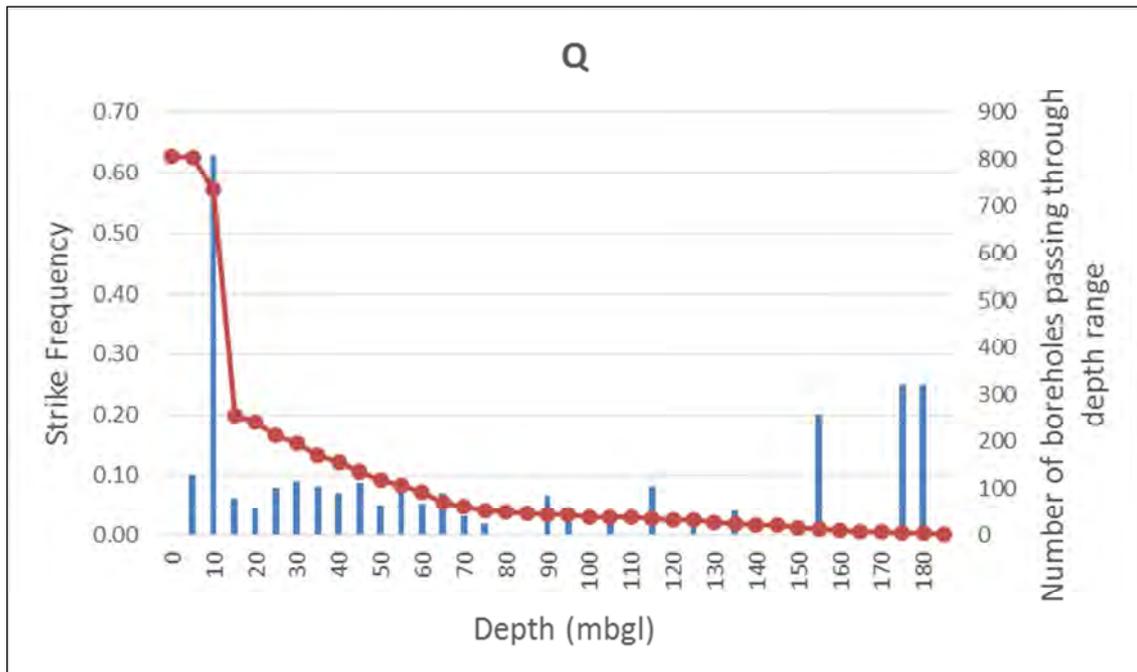


Figure 6-29: Q – Quaternary Deposits Strike Frequency.

Qb – Quaternary Deposits

Using a total of 103 borehole records, it is evident that the dominant strike frequency occurs at 10 mbgl and subsequently at 65 to 80 mbgl (Figure 6-30).

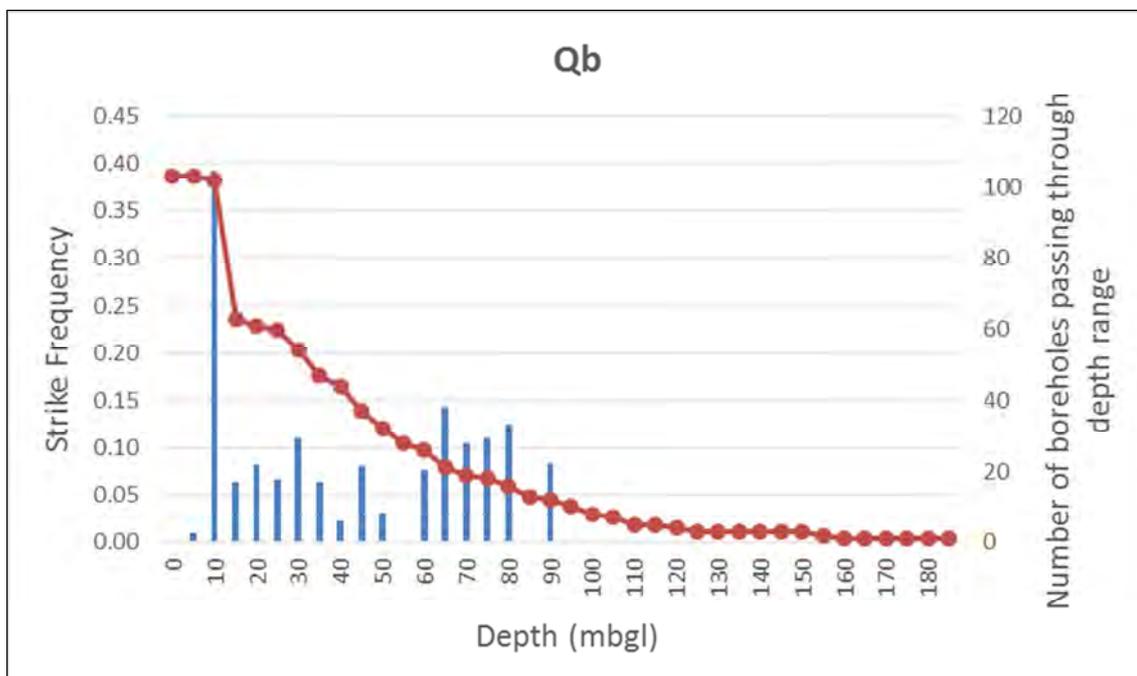


Figure 6-30: Qb – Quaternary Deposits Strike Frequency.

Qm – Strike Frequency

The dataset comprised 21 borehole records and indicates that the strike depth for Qm generally occurs between 10 to 30 mbgl (Figure 6-31).

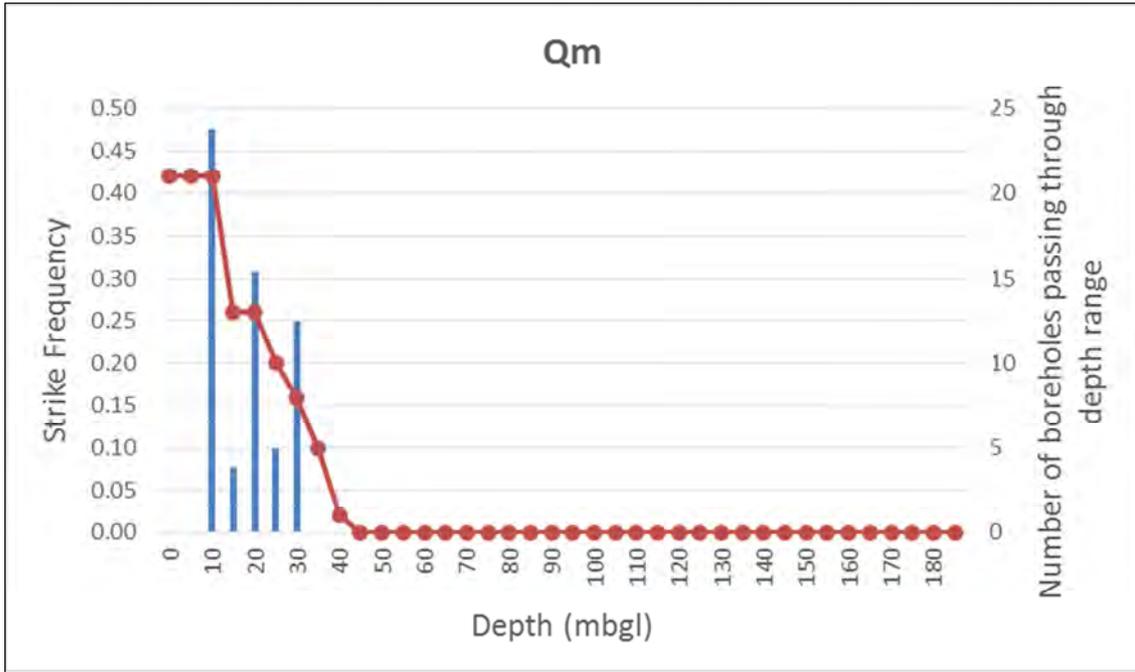


Figure 6-31: Qm Strike Frequency

Qs – Salnova Formation Strike Frequency

The analysis was undertaken on 940 borehole records which indicated that water strikes in Qs were frequently intercepted between 10 to 15 mbgl and is shown in Figure 6-32.

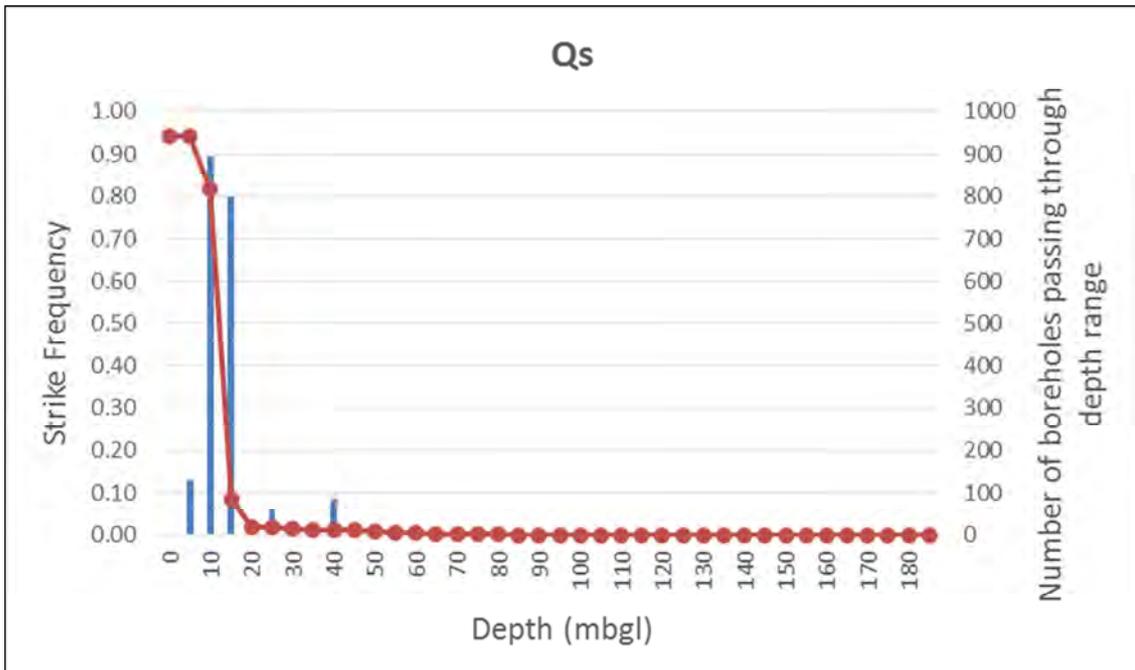


Figure 6-32: Qs Strike Frequency

Kz – Zululand Group Strike Frequency

Water strike information for the Kz lithology is limited to 13 borehole records and analysis of this data indicates that water strikes were intercepted at 25 and 80 mbgl (Figure 6-33). However due to limited data, the trend observed is regarded as conservative.

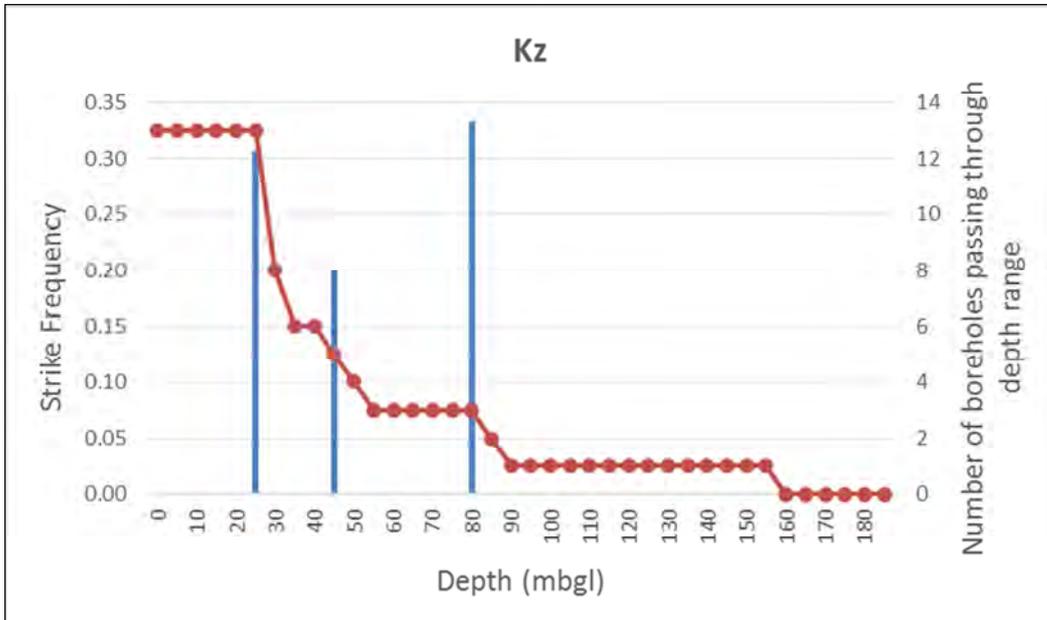


Figure 6-33: Kz - Zululand Group Strike Frequency

Ntu – Tuma Formation Strike Frequency

Similar to the Kz lithostratigraphic unit, water strike information is limited to 24 borehole records. Analysis of the water strike data indicates that water strikes are generally deep and are encountered at 145 and 155 mbgl as shown in Figure 6-34.

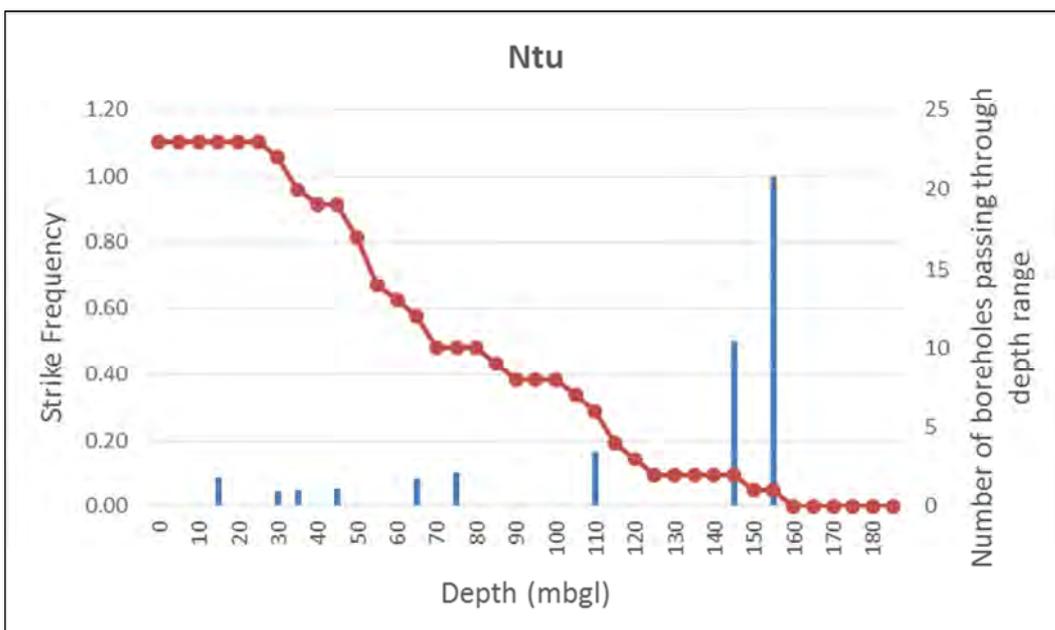


Figure 6-34: Ntu – Tuma Formation Strike Frequency

Pv – Vryheid Formation Strike Frequency

Similar to the Kz and Ntu lithostratigraphic units, information on water strikes was limited to 28 borehole records. Analysis of the water strike data indicates that water strikes are predominantly deep and occur at 65 mbgl. However, strikes intercepted between 20 to 30 mbgl (Figure 6-35) were also encountered and can possibly be attributed to local variation in the surrounding geology i.e. dolerite intrusions etc.

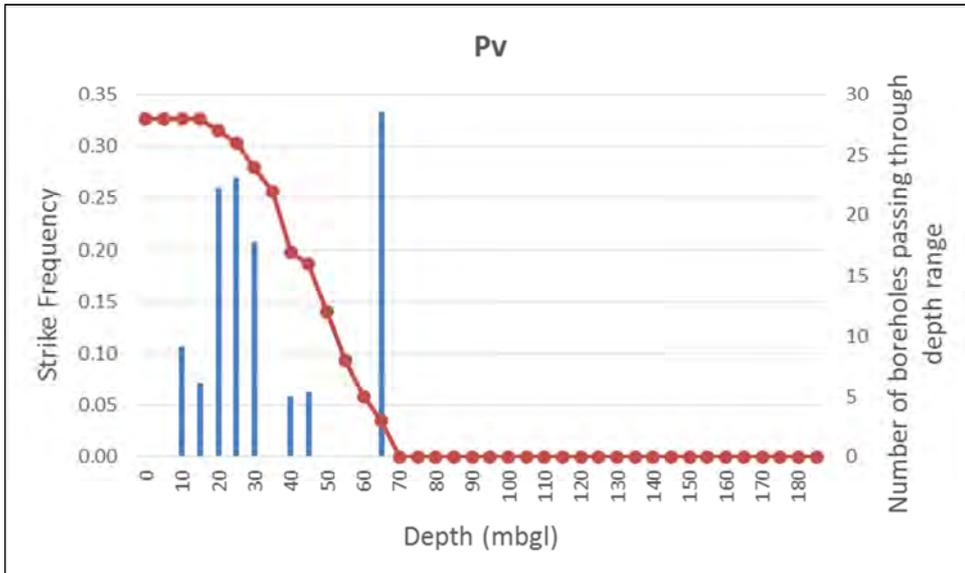


Figure 6-35: Pv – Vryheid Formation Strike Analysis

Pvo – Volksrust Formation

The Pvo dataset is very limited and comprises only 10 borehole records with water strike information. The dominant strike frequency occurs at 100 mbgl (Figure 6-36) and must be treated as conservative on account of limited data.

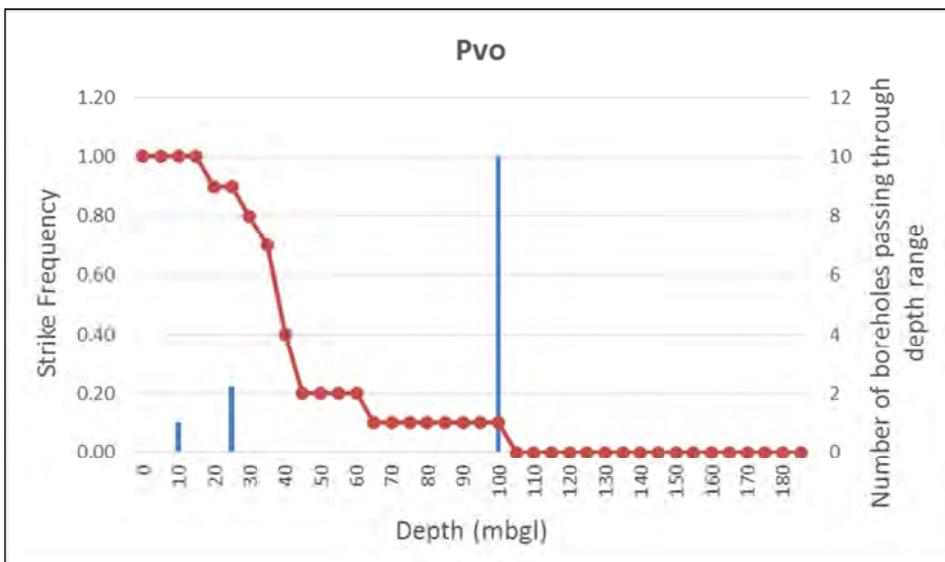


Figure 6-36: Pvo – Volksrust Formation Strike Frequency.

Zn – Nondweni Formation Strike Frequency

Fourteen borehole records with strike information were used in the analysis which indicates that the water strikes are generally intercepted at 95 mbgl. However, shallower water strikes are encountered from 25 to 60 mbgl (Figure 6-37).

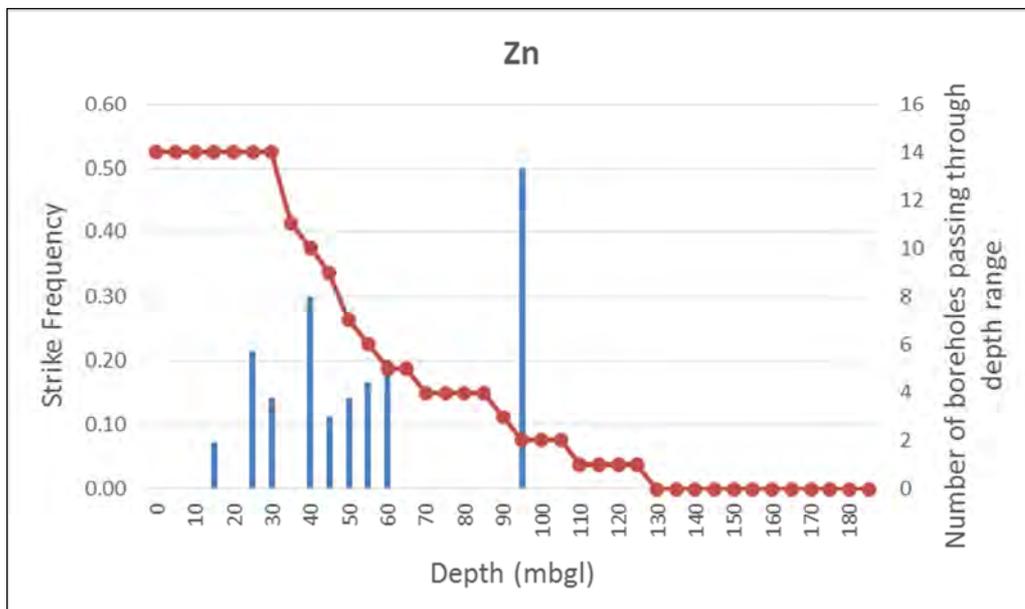


Figure 6-37: Zn – Nondweni Group Strike Frequency

6.1.7 Aquifer Parameters

The Aquifer Firm Yield Model (AFYM), (Murray *et al.*, 2012) was used to calculate the respective yields for each of the quaternaries (shown in Table 6-5) which define the study area. The AFYM provides insight into the groundwater potential for the ZCP.

According to Murray *et al.*, (2012), “the firm yield is defined as the maximum volume of water that can be guaranteed from a reservoir or aquifer during a critical dry period, which is often based on the lowest natural stream flow or recharge sequence on record”. To ensure longevity of the groundwater resource, the recharge and specific yield values of unconfined aquifer is fundamental.

Although the model uses time series rainfall and monthly evapotranspiration figures, the average parameters used for each quaternary catchment is presented in Table 6-5 and should be verified prior to utilisation.

According to the firm yield presented in Table 6-5, the W70A catchment has the highest groundwater potential of 4.57 Mm³/month followed sequentially by W32H (1.98 Mm³/month), W32B (1.79 Mm³/month), W12F (1.01 Mm³/month), W12J (0.74 Mm³/month), W23C (0.64 Mm³/month), W13B (0.55 Mm³/month) and W23D (0.47 Mm³/month).

Table 6-5: Input Parameters and Results for the Aquifer Firm Yield Model

Quaternary Catchment	Area (km ²)	MAP (mm/a)	Recharge (%)	Firm Yield (Mm ³ /month)
W12F	399.0	1,285	10.7	1.01
W12J	332.1	1,280	11.0	0.74
W13B	222.4	1,293	10.7	0.55
W23C	312.6	1,136	10.3	0.64
W23D	247.9	1,039	10.1	0.47
W32B	192.8	901	10.4	1.79
W32H	1,275.1	958	9.0	1.98
W70A	2,589.0	716	10.2	4.57

6.1.8 Geochemistry

The geochemical analysis discussed below is based on the water quality data derived from the GRIP dataset and reports from the private sector. The major cations and anions including pH and EC were analysed. Only lithostratigraphic units Qs, Qm and Q had ample chemistry data to warrant the presentation of Piper and Expanded Durov Diagrams which is shown in Figure 6-38 and 6-39, respectively.

According to Figure 6-38, it appears that lithostratigraphic units Q, Qs and Qm form distinct groups while Qb is relatively scattered. Similarly, this trend is also evident in Figure 6-39. The geochemical characteristics of the three groups comprising Q, Qs and Qm (displayed in Figure 6-38 and 6-39) are summarised below:

- Lithostratigraphic unit Q is marked by an alkaline pH. The chemical signature indicates enrichment in calcium (60 – 80%) which is accompanied by low concentrations in magnesium (20 – 40%). The anion composition comprised Cl which was at 20 – 40% and very low sulfate (<10%). Therefore, the dominant cation and anion are calcium and chloride, respectively and are likely to represent surficial deposits i.e. the Sibayi Formation (Section 3-7).
- Lithostratigraphic unit Qs is characterised by relatively neutral to weakly acidic pH. Sodium and potassium (Na & K) represent the major cations (>70%) while the anion signature is dominated by Cl (60 – 80%). The Na-Cl signature suggests direct recharge into the lithostratigraphic unit.
- Lithostratigraphic unit Qm has neutral to weakly acidic pH. This unit has relatively equal composition of sodium, potassium and calcium (c.40%) however the chloride concentration is exceptionally high (>80%) with SO₄ <20%.

Based on the above, the geochemistry of the three distinct groups suggests that they are likely to represent unique geological units with distinct hydrogeological properties.

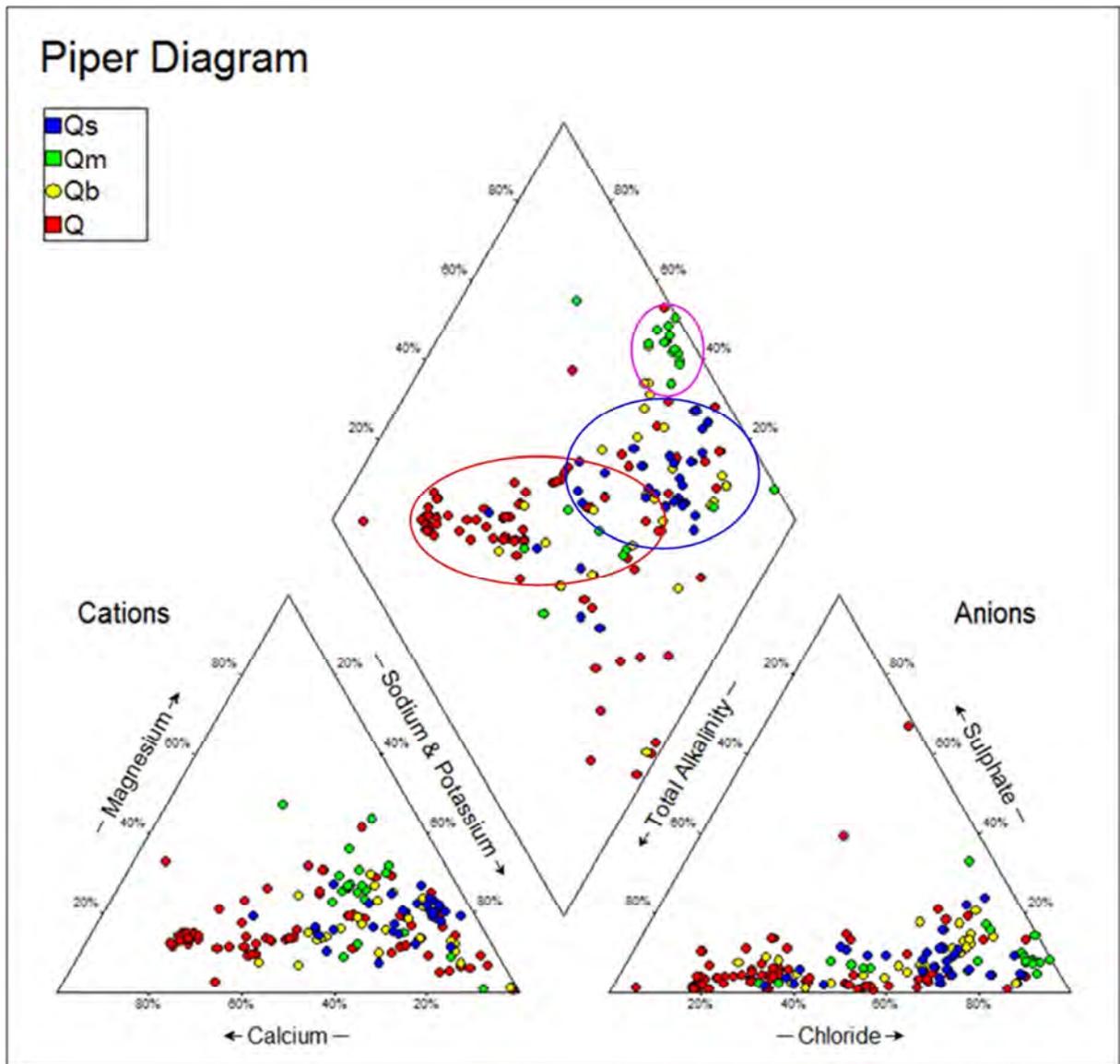


Figure 6-38: Piper Diagram for Lithostratigraphic Unit Q, Qs, Qm and Qb.

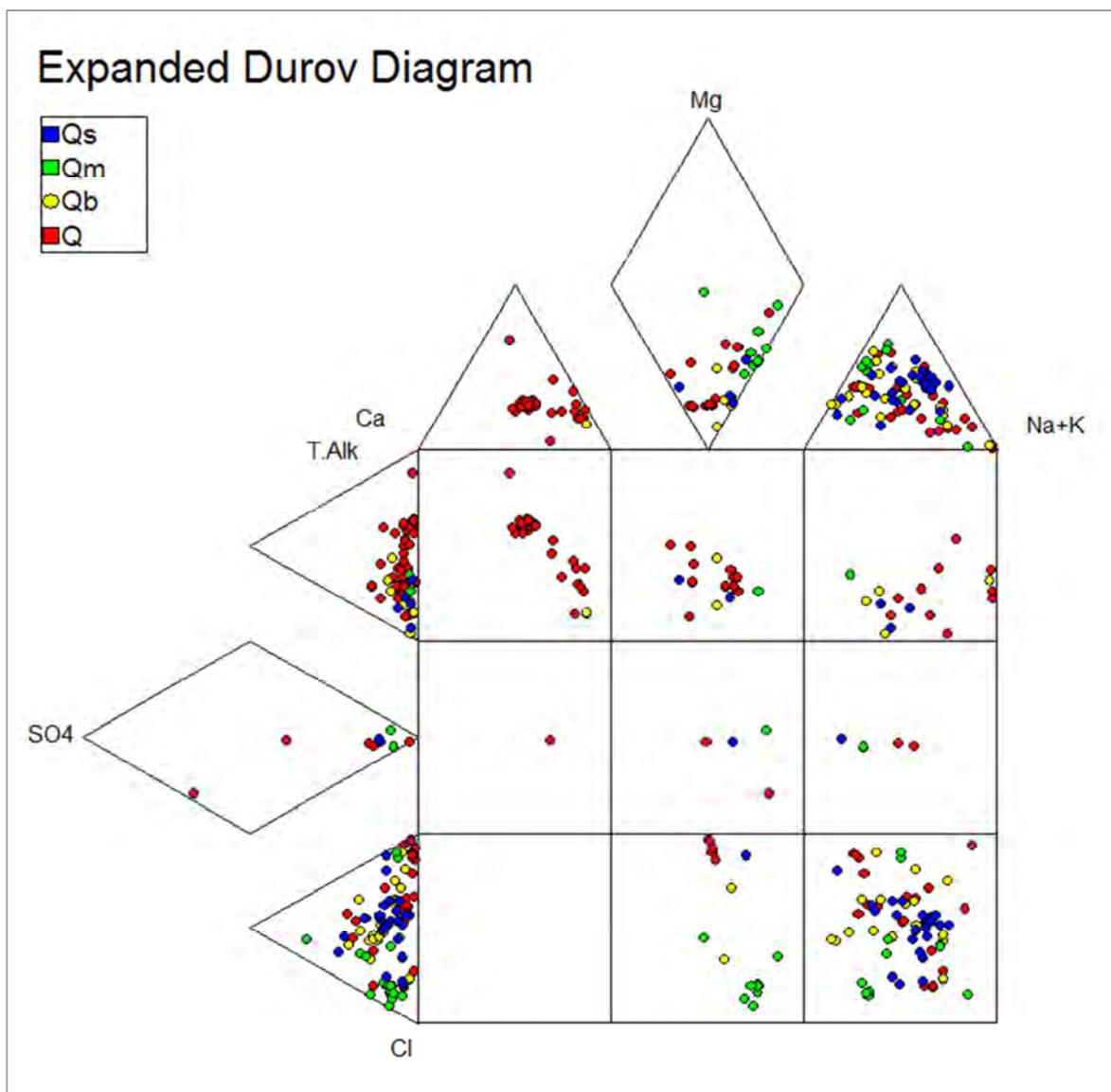


Figure 6-39: Expanded Durov Plot for Lithostratigraphic Unit Q, Qs, Qm and Qb.

6.2 Delineation of Hydrostratigraphic Units

Vegter (2001) provided details regarding the delineation of the primary groundwater regions in South Africa and the statistical analyses to be conducted. However, Vegter (2001) did not provide details on how to divide the primary groundwater region into sub-regions. Therefore an approach had to be developed for this study.

The only guidelines provided by Vegter (2001) were to include the basic lithology, geological and hydrogeological statistics and geochemical analysis to assess water quality trends. Unfortunately as already mentioned, there is limited geochemical data available for the study area. Based on the above, similar stratigraphic units (on a lateral or horizontal level) were grouped together as presented in Table 6-6 and shown in Figure 6-40.

Table 6-6: Lateral Delineation of Hydrostratigraphic Units based on Geology

Acronym	Lithostratigraphic Unit	Sub-region
Q	Quaternary Age Deposits	1
Qpd	Quaternary Age Deposits	3
Qb	Bluff Formation	1
Qm	Masotcheni Formation	2
Qs	Salnova Formation	6
Tu	Uloa Formation	8
Kz	Zululand Group	4
Jl	Lebombo Group	5
Nhl	Hlobane Complex	7
Nng	Nigramoep Formation	7
Ntu	Tuma Formation	9
Pv	Vryheid Formation	4
Pvo	Volksrust Formation	4
ZB	Unnamed potassic granite and gneiss	7
Zn	Nondweni Formation	5

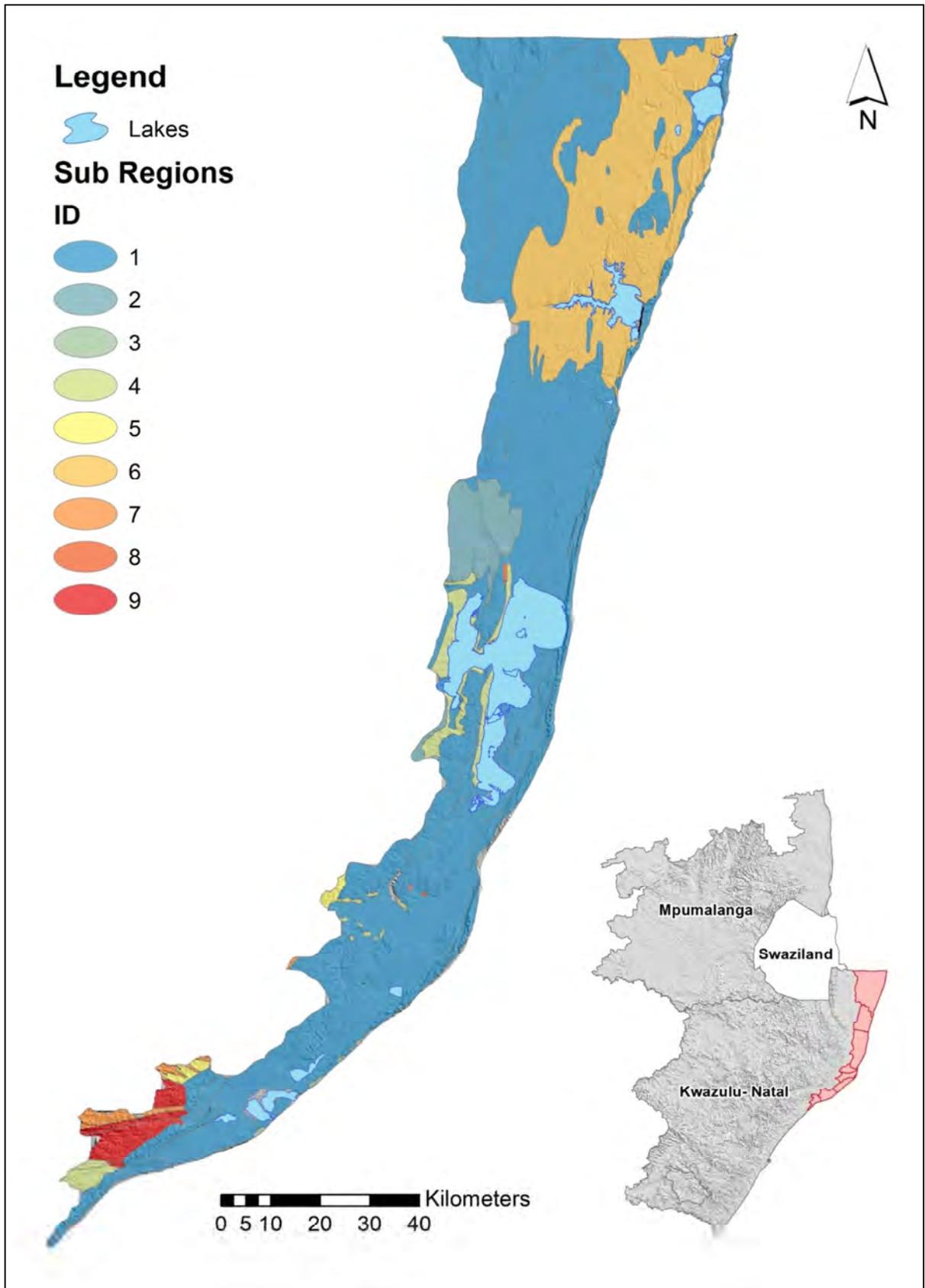


Figure 6-40: Lateral Delineation of Hydrostratigraphic Units Based on Geology.

The borehole yields for the lateral hydrostratigraphic units shown in Table 6-6 are presented in Table 6-7. The borehole yield documented in Table 6-4 was rated as:

- Greater than or equal to 10 L/s = high.
- Between 5 and 10 L/s = medium.
- Less than 5 L/s low.

The borehole yields were used to confirm the delineation of the respective sub-regions.

Table 6-7: Delineation of Lateral Sub-regions Based on Geological Statistics

Acronym	Sub-region	Borehole yield
Q and Qb	1	High; high
Qm	2	Medium
Qpd	3	No data
Kz, Pv and Pvo	4	Low; low; low
Jl and Zn	5	No data; low
Qs	6	High
Nhl, Nng and ZB	7	No data; no data; no data
Tu	8	No data
Ntu	9	Low

Vegter (2001) did not provide any guidelines for the vertical delineation of hydrostratigraphic units however this aspect must be considered on account of the limited data and the regional geology discussed in Section 3-7.

Interpretation of the geostatistical analysis undertaken in Chapter 6-1 indicates that there are distinct trends associated with the respective lithostratigraphic units as displayed in Table 6-8. Based on the trends observed in Table 6-8, Figure 6-38 and Figure 6-39, lithostratigraphic units which had sufficient borehole records and adequate aerial extent were used to delineate three vertical hydrostratigraphic units. The vertically delineated hydrostratigraphic units were then chronologically aligned with the respective stratigraphic units discussed in Section 3-7.

Borehole records for the Uloa Formation were restricted to two records therefore geostatistical analyses and subsequent delineation could not be undertaken. However, an additional hydrostratigraphic unit representing the Uloa Formation was included on account of its productiveness when intercepted, as documented by several literature sources (Worthington, 1978; Meyer *et.al.*, 2001; Cobbing *et al.*, 2008).

The Zululand Group is referred to as the hydrogeological basement for the ZCP, (Worthington, 1978; King, 1997; Meyer *et.al.*, 2001). Data for the Zululand Group is limited

to a total of thirteen borehole records (Table 6-8). On account of its low yield, saline water quality and hydrogeological properties, the Zululand Group aquifer is unsuitable for exploitation. Based on the discussions above, the Zululand Group will be discussed solely in the context of representing the hydrogeological basement for the ZCP and will not be regarded as one of the hydrostratigraphic units delineated as part of this dissertation.

Table 6-8: Vertical Delineation of Hydrostratigraphic Units

Acronym	No. of Borehole Records	Area (%)	Average Borehole Depth (mbgl)	Water Strike Depth (mbgl)	Yield (L/s)	Discharge (L/s)	Delineated Hydrostratigraphic Unit
Q	807	54.2	22.0	10	16.91	1.69	Hydrostratigraphic Unit 1
Qb	103	14.3	37.3	10	11.46	0.77	
Qs	940	21.1	7.8	10 – 15	18.92	5.92	Hydrostratigraphic Unit 2
Qm	21	3.9	19.4	10 - 30	7.35	1.47	Hydrostratigraphic Unit 3
Tu	-	-	-	-	-	-	Hydrostratigraphic Unit 4
Kz	13	2.4	47.7	25 and 80	0.02	0.10	N/A: Hydrogeological basement for the ZCP.

'-' Denotes insufficient data (2 borehole records) available.

'N/A' Denotes not applicable.

The vertically delineated hydrostratigraphic units for Groundwater Region 65 are discussed below:

6.2.1 Hydrostratigraphic Unit 1

Hydrostratigraphic Unit 1 represents the Sibayi Formation. Maud (1980) referred to the Sibayi Formation as the surficial sands of the ZCP as they comprise of medium sized, well rounded grains that are unconsolidated. The aeolian deposit forms the coastal barrier dune complex, (Hobday, 1979).

According to Table 6-8, hydrostratigraphic unit 1 is the most extensive aquifer. The laterally extensive sands occur in most areas however its thickness is variable across the ZCP.

6.2.2 Hydrostratigraphic Unit 2

Hydrostratigraphic Unit 2 represents the Kwabonambi Formation which is characterised by high silt and clay. Worthington (1978) indicated that the Kwabonambi Formation are unconsolidated sands while Botha (1997) described the Kwabonambi Formation as decalcified dune sediments derived from the alteration of older dune sands, inter-dune

wetland deposits and freshwater diatomite accumulations which can account for the high yields when intercepted.

In the absence of hydrostratigraphic unit 1, hydrostratigraphic unit 2 caps the dune cordons to form a perched aquifer associated with high surface elevations. Hydrostratigraphic unit 2 occurs in certain areas in the ZCP and represents the most prominent perched aquifer in the study area. Spatial variability with respect to thickness is also noted.

6.2.3 Hydrostratigraphic Unit 3

Hydrostratigraphic Unit 3 comprises semi-consolidated sand intercalated with clay and lignite of the Kosi Bay and Port Dunford Formation's. The Kosi Bay Formation comprises semi-consolidated orange to grey, weathered sand dunes with intercalated lenses of clay and lignite which overlie the Port Dunford Formation and is assumed to cover most of the ZCP, (Hobday and Orme, 1974).

The Port Dunford Formation comprises basal coarse beach rocks overlain by mud, lignite and capped by a thin layer of marine sands. Maud and Orr (1975) suggest that the Port Dunford Formation consists of laterally discontinuous layers of mixed facies while Kelbe and Germishuys (2001) indicated that the Port Dunford Formation was extensive in comparison to the Uloa Formation and was present beneath most of the coastal barrier complexes.

Hydrostratigraphic unit 3 is erratically distributed across the ZCP and when present, is typically lenticular in shape and laterally discontinuous. In the absence of both hydrostratigraphic unit 1 and 2, hydrostratigraphic unit 3 forms a perched aquifer which gives rise to wetlands however this phenomenon is localised.

6.2.4 Hydrostratigraphic Unit 4

Hydrostratigraphic Unit 4 consists of coquina and calcarenite of the Uloa Formation. The Uloa Formation consists of a basal conglomerate bed followed by a lower coquina and an upper calcarenite layer. The upper surface of the coquina limestone is yellow-brown in colour suggesting that it was leached by karst solution weathering prior to the deposition of the calcarenite. The lower portion of the calcarenite is coarse grain and well-bedded in comparison to the aeolian deposited upper section, (Maud and Orr, 1975; Worthington, 1978; Lui, 1995).

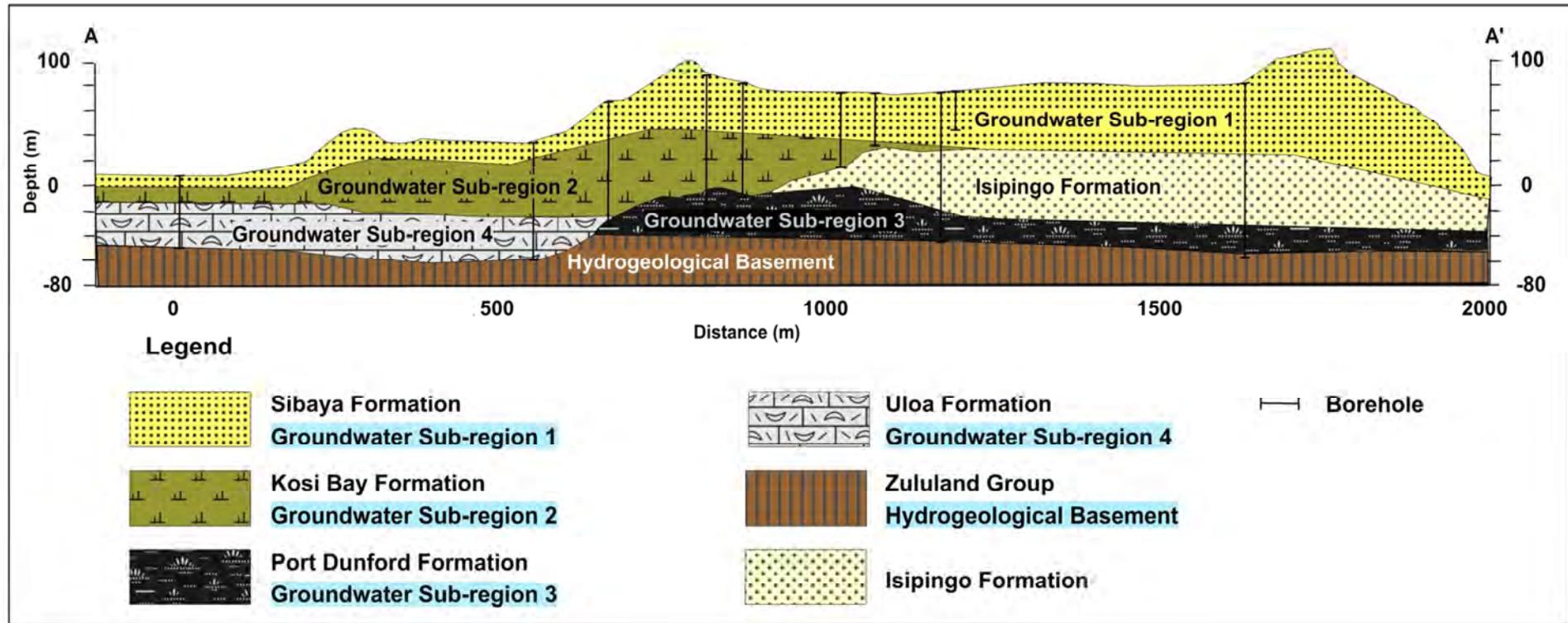
The Uloa Formation has very limited occurrence. When present, the Uloa Formation or hydrostratigraphic unit 4 is irregularly distributed across the ZCP and is generally in contact with hydrostratigraphic unit 3. The thickness of the hydrostratigraphic unit 4 is also highly variable across the ZCP.

6.2.5 Hydrogeological Basement of the ZCP

The siltstone and sandstone of the Zululand Group represents the hydrogeological basement of the ZCP. The Zululand Group shows a typical upward fining sequence of deposits ranging from basal conglomerates, cross-bedded sandstone, marls and eventually siltstone, (Hobday, 1979).

Similar to hydrostratigraphic unit 3 and 4, the Zululand Group is sporadically distributed. When present, the Zululand Group occurs at shallow depths in the northern areas of the ZCP in comparison to its occurrence in the southern-southeastern areas of the ZCP.

It is important to note that with regards to the spatial distribution of the four hydrostratigraphic units, hydrostratigraphic unit 1 and 2 have extensive occurrence while the distribution of the remaining hydrostratigraphic units are limited, erratic and discontinuous across the ZCP. Therefore, boreholes are unlikely to intercept all four hydrostratigraphic units in a vertically, sequential manner as listed in Table 6-8. The localised distribution of the vertically delineated hydrostratigraphic units is shown in Figure 6-41.



6.3 Hydrogeological Characteristics for the Vertically Delineated Hydrostratigraphic Units

It is evident that based on the discussions presented thus far in this dissertation, the respective vertical hydrostratigraphic units delineated can be categorised either as shallow or deep aquifers. Detailed discussions on the hydrogeological properties for the four vertically delineated hydrostratigraphic units including the hydrogeological basement for the ZCP, all of which are either classified as shallow or deep aquifers, are presented in the sections below.

6.3.1 Shallow Aquifers

Davies *et al.*, (1992) indicated that the grain size distribution and porosity of the young surficial sands, older cemented aeolian sands and the Port Dunford Formation can be regarded as essentially the same. The only differentiator in the aforementioned deposits is the variation in the volume of the silt and clay. Therefore, on account of geological similarities and water levels analyses (Section 6-1.3), hydrostratigraphic unit 1 to 3 can be regarded as the 'shallow aquifer' for the study area as summarised below:

- Hydrostratigraphic unit 1: Cover sands of the Sibayi Formation.
- Hydrostratigraphic unit 2: Silty sands of the Kwabonambi Formation.
- Hydrostratigraphic unit 3: Semi-consolidated Kosi Bay and Port Dunford Formation's.

Hydrostratigraphic unit 1 (Cover Sands – Sibayi Formation)

The surficial sands are an aeolian deposit which consists of medium, well rounded grains that vary from unconsolidated to loosely consolidated, (Maud, 1980) and are distributed across the ZCP with the exception of the drier western portions which are in close proximity to the Lebombo Mountains, (DWAF, 2004). According to Table 6-8, hydrostratigraphic unit 1 encompasses an area of c.69% of the ZCP.

Data analyses presented in Section 6-1.3 indicates that the majority of borehole records contain water levels which are predominantly <5 mbgl (Figure 6-2 and 6-4) and confirms the presence of a shallow aquifer. The strike frequency for lithostratigraphic unit Q was undertaken using 807 borehole records and according to Figure 6-29, the dominant strike frequency occurs at 10 mbgl.

A Bayesian correlation coefficient of 0.97 for the boreholes recorded in the geological dataset confirms that the groundwater levels display a very good correlation with topography (Figure 6-3).

According to Parsons (1995), borehole yields in unconsolidated coastal deposits are highly variable and are a function of the grain size and thickness. Geostatistical analyses of 696

borehole records indicated that the typical yields associated with lithostratigraphic unit Q i.e. hydrostratigraphic unit 1 was at 16.91 L/s, of which 81 boreholes were operated at rate of an average of 1.69 L/s (Table 6-4 and Figure 6-27). However, heterogeneities in the aquifer are expected to occur. This is confirmed by DWAF (2004) who reported that the shallow aquifer was extensively utilised as a domestic water supply by rural communities across the ZCP, via a series of shallow unlined wells, shallow concrete ring-supported open wells and recently shallow tube wells which are equipped with hand pumps on account of their low yields (Figure 6-42). According to Table 6-8, low discharge rates of an average of 0.77 L/s were reported for the Qb lithostratigraphic unit

According to King (1997), hand dug wells are common in rural areas across the ZCP as they exploit the shallow and or unconfined aquifer. Hand dug wells are characterised by a wide diameter and generally do not exceed 20 mbgl. Analyses and interpretation of boreholes records captured on the GRIP database confirmed that c.1,360 records had borehole diameters between 200 to 220 mm.



Figure 6-42: Utilisation of the Shallow Aquifer (Hydrostratigraphic unit 1).

In an attempt to obtain a coarse estimate of the expected transmissivity (T) of hydrostratigraphic unit 1, the transmissivity was calculated using the aforementioned borehole yields and the qualified guess discussed in Chapter 4-1 (i.e. $T = 10 \cdot Q$; Van Tonder *et al.*, 2002). Therefore, the transmissivity value for the borehole records categorised as hydrostratigraphic units 1 in the geological dataset was calculated at c.169 m²/d. This T -value is relatively similar to Worthington (1978) who through pump

testing of several boreholes calculated an average T-value of 140 m²/d for the surficial sands. However, one must cognisant of areas which have reduced T-values of c.7 m²/d which can be attributed to possible heterogeneities in the aquifer.

The aeolian deposit expansive across the ZCP is highly porous and permeable. Porosity ranged from 23% to 38% while permeability values ranged from 0.8 to 17 m/d (Table 6-9). Parsons (2004) referred to the surficial sands as a primary porosity aquifer. Due to its porous nature, Worthington (1978) calculated a vertical leakage coefficient of 0.5 m/d towards the underlying lithologies. Worthington's (1978) study concluded that the saturated fine sands, which had an estimated saturated thickness of 6 m, were extremely porous and had very little ability to attenuate vertical groundwater movement and therefore directly recharged the lower formations.

Table 6-9: Aquifer Parameters Cited for Hydrostratigraphic unit 1

Reference	Worthington (1978)	Davies <i>et al.</i> , (1992)	Meyer and Godfrey (1995)	Meyer <i>et al.</i> , (2001)	Schapers (2011)	Jeffares and Green (2012)
Geological Formation⁷		Cover sands				
Yield (L/s)	-	-	-	-	5.25 to 10.78	2.2 to 25
Transmissivity (m²/d)	140	-	-	-	75 to 500	10 to 5,544
Horizontal K (m/d)	-	-	15.5	-	-	-
Vertical K (m/d)	3.2	-	-	-	-	-
Storativity	-	-	-	35	-	-
Permeability (m/d)	-	0.8 to 17	-	15.6	-	-
Porosity (%)	-	38	-	23	-	-

‘-’ Denotes no data available.

Rawlins (1991) suggested that the permeability and porosity of the surficial sands decreased with depth on account of compaction. Parsons (1995) indicated that primary aquifers typically have storativity values ranging from 0.1 to 0.2.

Meyer and Godfrey (1995) estimated that the horizontal hydraulic conductivity (K) of the cover sands was at 15.5 m/d while Grundling and Grundling (2010) calculated a hydraulic conductivity of 8.64 m/d for the Sibayi Formation. Worthington (1978) calculated a vertical K-value of 3.2 m/d suggesting the both the vertical and horizontal hydraulic conductivity in

⁷ The column labelled ‘Geological Formations’ in Table 6-9 to 6-12 refers to the geological formation as cited in the respective literature references.

the formation were high. Seepage from the shallow aquifer sustains several lakes, pans, streams and shallow peat swamps which extensively occur across the ZCP, (DWAF, 2004).

The surficial sands which represent remobilisation within the Sibayi Formation are typically, shallow and leached thus containing low nutrient content, (Watkeys *et al.*, 1993). Based on Section 6-1.8, hydrostratigraphic unit 1 has relatively neutral to alkaline pH (average pH of 7.17) and low EC (average of 54.51 mS/m). According to Figure 6-38 and Figure 6-39, the cover sands are enriched in calcium (Ca) and are consistent with findings of Hobday (1979) who described the Sibayi Formation as a calcareous homogenous aeolian deposit. Barring calcium, sodium (Na) and chloride (Cl) are the dominant cation and anion, respectively. The aforementioned chemical signature can possibly be attributed to the highly permeable nature of the sands which promotes rapid recharge from precipitation, (WRC, 2011) or direct recharge from surface water resources, (Mkhwanazi, 2010).

King (1997) analyses of the nine water samples collected from the surficial sands confirmed the relatively alkaline pH (average pH of 7.5) and dominant Na-Cl signature as the average Na and Cl concentration was reported at 127.4 mg/L and 217.2 mg/L, respectively.

The cover sands form a veneer across the ZCP and on account of its primary porosity, its laterally extensive distribution and relatively good water quality, the Sibayi Formation (representing hydrostratigraphic unit 1) is classified as a major primary porosity aquifer, (Parsons, 2004).

Hydrostratigraphic unit 2 (Kwabonambi Formation)

Commonly referred to as the 'older aeolian sands', the Kwabonambi Formation (hydrostratigraphic unit 2) comprises unconsolidated sand, silts, clay and organic matter, (Worthington, 1978). These layers and lenses have distinct hydraulic properties and can be expected to influence groundwater flow and direction, (Rawlins, 1991).

Geostatistical analyses of the water level data (Figure 6-11 and 6-12) for the Qs lithostratigraphic unit i.e. hydrostratigraphic unit 2, indicates the presence of two aquifer systems. The majority of water level data is associated with shallow water levels (<5 mbgl) which is likely to be attributed to a reduced silt and clay content with the latter associated with water levels at c.10 mbgl. However, both systems have a correlation coefficient of 0.99 which suggests that groundwater flow mimics topography (Figure 6-9).

The average borehole depth intercepting Qs lithostratigraphic unit i.e. hydrostratigraphic unit 2, is at 7.8 mbgl (Table 6-3) and the average borehole yield calculated from 937 records was 18.92 L/s. However, only three boreholes recorded a discharge rate of 5.92 L/s (Table 6-4).

Recent studies undertaken by Jeffares and Green (2012) revealed that borehole yields in excess of 25 L/s can be achieved via the installation of deep, large diameter, screened boreholes into sandy alluvium in the lower coastal portions. The critical factor in generating high yields are the presence of medium to coarse grain size sand, (DWAF, 2004). This scenario is demonstrated by Jeffares and Green (2012), as boreholes intercepting medium to coarse grain sand in low lying areas generated a yield of 10 to 20 L/s (boreholes SODO5B and SODO6B). Therefore, it appears that the average borehole yield of 18.92 L/s may possibly be attributed to the geological phenomenon discussed above which has localised occurrence.

Further to this, Schapers (2011) and Jeffares and Green (2012) reported T-values ranging from 75 to 500 m²/d and 10 to 5,544 m²/d, respectively (Table 6-10). Schapers (2011) suggested that the high T-values in conjunction with shallow but significant hydraulic gradients are indicative of short residence time in the aquifer. However, one must regard the aforementioned T-values as the exception rather than the norm on account of local heterogeneities in the aquifer media.

According to literature sources (Table 6-10), porosity remains high at 37.9% and the horizontal hydraulic conductivity of the older aeolian sands ranged from 0.87 to 17 m/d. Worthington (1978) calculated a vertical hydraulic conductivity ranging from 0.2 to 0.5 m/d and vertical leakage coefficient ranging from 2 to 5 x 10⁻² m/d and therefore classified the Lower Kwabonambi Formation as an aquitard.

Table 6-10: Aquifer Parameters Cited for Hydrostratigraphic unit 2

Reference	Worthington (1978)	Davies <i>et al.</i> , (1992)	Meyer and Godfrey (1995)
Geological Formation	Lower Aquiferous sands	Older Aeolian sands	
Yield (L/s)	-	-	-
Transmissivity (m²/d)	-	-	-
Horizontal K (m/d)	16	-	-
Vertical K (m/d)	0.2 to 0.5	-	0.87
Storativity	3.3 x 10 ⁻³	-	-
Permeability (m/d)	-	0.8 to 17	-
Porosity (%)	-	37.9	-

⁻ Denotes no data available.

When compared to the hydrogeological properties of hydrostratigraphic unit 1, hydrostratigraphic unit 2 has reduced permeability and hydraulic conductivity which are attributed to increased silt and clay content, (Rawlins, 1991). The reduced permeability of

the silts and clay tend to restrict groundwater flow thus giving rise to perched aquifers as depicted by the unconfined water table which is typically associated with elevated surface topography, (Jeffares and Green, 2012).

The shallow to perched groundwater table permits groundwater utilisation via shallow hand dug wells which are equipped with hand pumps to serve numerous rural communities across the ZCP, (Meyer *et al.*, 2001). More than 96% of the boreholes recorded on the GRIP dataset for the Qs lithostratigraphic unit i.e. hydrostratigraphic unit 2 had a diameter of 200 mm which confirms the use of wide diameter boreholes to intercept the shallow groundwater table. Figure 6-43 displays a perched pan which has been regularly used for water supply by local inhabitants for many years, (Kelbe and Germishuys, 2010) and is assumed to represent hydrostratigraphic unit 2.

Mkhwanazi (2010) indicated that the water chemistry of the Kwabonambi Formation was weakly acidic (pH range of 4.73 to 5.57) and enriched in iron (40 to 82 mg/L). The weakly acidic pH was confirmed by the geochemical analysis (Section 6-1.8) and is shown in Figure 6-38.



Figure 6-43: A Perched Pan used for Domestic Purposes, (Kelbe and Germishuys, 2010).

Hydrostratigraphic unit 3 (Kosi Bay and Port Dunford Formation)

Parsons (2004) defined perched aquifers as “saturated groundwater that overlies an unsaturated zone. Perched aquifers are localised and occurs when the underlying formation has low hydraulic conductivity than the saturated water body which retards the vertical movement of groundwater. Wetlands, springs and seeps manifest when the perched aquifer discharges at the surface. Also, groundwater discharge occurs in and round riparian zones”, (Parsons, 2004).

These features are demonstrated by the expansive wetlands which occur in close proximity to Kosi Bay and Lake St. Lucia as the exposed clay enriched Kosi Bay profile located in broad bottomlands forms a perched water table, (Botha and Porat, 2007). Therefore, hydrostratigraphic unit 3 can be regarded as a perched aquifer of localised occurrence as it only accounts for an area of 3.9% in the ZCP (Table 6-8). The limited aerial extent can possibly be attributed to the erratic distribution of the discontinuous layers of the Kosi Bay and Port Dunford Formation.

Borehole data intercepting lithostratigraphic unit Qm i.e. hydrostratigraphic unit 3 is limited to 21 boreholes which have an average depth of 19.4 mbgl. Lithostratigraphic unit Qm reported an average yield of 18.92 L/s (16 records) and discharge rate of 1.47 L/s (7 records). However, these values must be regarded as conservative on account of the limited data. Water strikes were encountered between 10 and 30 mbgl and corresponds with two semi-confined systems which were identified in Figure 6-8. Both systems displayed a high correlation between water level and surface topography (Figure 6-9).

According to Table 6-11, the porosity and permeability of the Port Dunford Formation ranged from 31 to 42.3% and 0.8 to 5 m/d, respectively. Transmissivity was calculated at 0.2 to 0.5 m²/d, while horizontal hydraulic conductivity was at 4.3 m/d and vertical hydraulic conductivity at 0.05 m/d.

Table 6-11: Aquifer Parameters Cited for Hydrostratigraphic unit 3

Reference	Worthington (1978)	Davies <i>et al.</i> , (1992)	Meyer and Godfrey (1995)	Meyer <i>et al.</i> , (2001)
Geological Formation	Port Dunford Formation			
Yield (L/s)	-	-	-	-
Transmissivity (m²/d)	-	-	-	0.2 to 0.5
Horizontal K (m/d)	-	-	4.3	-
Vertical K (m/d)	0.05	-	-	-
Storativity	-	-	-	20
Permeability m/d)	-	0.8 to 17	-	4 to 5
Porosity (%)	-	42.3	-	31

¹ Denotes no data available.

On account of its low transmissivity and strong adhesive forces, the Port Dunford Formation and in some instances, the Kosi Bay Formation retards rapid vertical migration of groundwater, (Jeffares and Green, 2012). According to Worthington (1978), an average vertical leakage coefficient of 7.3×10^{-3} m/d recharged the underlying Uloa Formation and therefore, the Port Dunford Formation (hydrostratigraphic unit 3) was considered an

aquitard. In addition, Jeffares and Green (2012) regarded the Kosi Bay and Port Dunford Formation's as a confining or semi-confining layer to the underlying geological formations.

Based on the geochemical analysis undertaken in Section 6-1.8, the pH ranged from 4.99 to 6.72 thus indicative of relatively neutral to weakly acidic conditions (Figure 6-38). EC was low (<73 mS/m).

Water samples representative of the Kosi Bay and Port Dunford Formation were analysed by Mkhwanazi (2010). The Kosi Bay water samples were leached and enriched in organic matter which is thought to have accelerated the acidity (average pH of 5.21). The water chemistry was characterised by the presence of high iron and silica which is assumed to be associated with the weathering of sediments and clay minerals in the geological formations.

Mkhwanazi (2010) analyses further revealed that groundwater in the Port Dunford Formation was predominantly acidic (pH ranged from 3.6 to 4.71) and depleted in bicarbonate ions. The signature of the Port Dunford Formation was characterised by low concentrations of magnesium (<31 mg/L), sulphate (2 to 119 mg/L) and potassium ions (<17 mg/L) and a high concentration of iron (35 to 206 mg/L). The findings of Mkhwanazi (2010) are relatively consistent with the water quality trends derived from the geological dataset.

6.3.2 Deep Aquifers

The Uloa Formations (hydrostratigraphic unit 4) and the Zululand Group (hydrogeological basement) represent the deep aquifers in Groundwater Region 65.

Lithostratigraphic unit Tu on Figure 6-1 (Uloa Formation i.e. hydrostratigraphic unit 4) could not be delineated in the same manner as undertaken for lithostratigraphic units Q, Qm and Qs on account of the limited data (two borehole records). However, the literature review (Section 2) suggested that the Uloa Formation is of hydrogeological significance therefore; a summary of its hydrogeological characteristics is presented below.

Hydrostratigraphic unit 4 (Uloa Formation)

The coquina and calcarenite of hydrostratigraphic unit 4 exhibits porosity values in the magnitude of 20 to 50% (Table 6-12). Worthington (1978) indicated that the Uloa Formation had an effective porosity of 20% which is further enhanced by karst solution weathering. Permeability of the Uloa Formation ranged from 0.5 to 23.6 m/d with an average of 4.5 m/d, (Meyer *et al.*, 2001).

Boreholes intercepting the Uloa Formation are exploited via the installation of fully cased and basally screened boreholes, (DWAF, 2004). According to Table 6-12, the boreholes generated yields ranging from 0.45 to 30 L/s and are therefore indicative of T-values in the order of 5.5 to 1,500 m²/d. Similarly, the horizontal hydraulic conductivity of the formation is

also high and ranged from 1.3 to 4.5 m/d. Storativity in the aquifer ranged from 1.9×10^{-5} to 5.7×10^{-4} .

According to Schapers (2011), field observations documented during the drilling of several investigative boreholes indicated that the Uloa Formation contained abundant shell fragments and displayed variation in vertical thickness over a distance of 15 m. Dry boreholes were intercepted in areas where the calcrete was strongly cemented and dissolution channels were absent, (Schapers, 2011). Based on the above, it is deduced that the Uloa Formation displays lateral and vertical heterogeneity.

Table 6-12: Aquifer Parameters Cited for Hydrostratigraphic unit 4

Reference	Davies <i>et al.</i> , (1992)	Worthington (1978)	Meyer and Godfrey (1995)	Meyer <i>et al.</i> , (2001)	Cobbing <i>et al.</i> , (2008)	Schapers (2011)	Jeffares and Green (2012)
Geological Formation	Uloa Formation						
Yield (L/s)	-	-	25	25	30	2.25 to 9.25	0.45 to 17.5
Transmissivity (m²/d)	-	5 - 40	-	-	>1,000	58 to 1,500	5.1 to 587.6
Horizontal K (m/d)	-	1.3 to 2.5	-	4.5	-	-	-
Vertical K (m/d)	-	0.1	-	-	-	-	-
Storativity	-	5.7×10^{-4}	-	1.9×10^{-5} to 4.7×10^{-3}	-	-	-
Permeability (m/d)	-	-	-	0.5 to 23.6 Average - 4.5	-	-	-
Porosity (%)	42	20	-	50	-	-	-

-' Denotes no data available.

The upper boundary of the Uloa Formation comprises relatively impermeable clay lenses of the Port Dunford Formation. Therefore, the Uloa Formation can be regarded as semi-confined to confined aquifer, (Mkhwanazi, 2010). In addition, several pump tests undertaken by Meyer *et al.*, (2001) revealed that the Uloa Formation frequently displayed leaky confined aquifer conditions.

King (1997) hypothesised that the fine grain sediments of the Kosi Bay and Port Dunford Formation's recharged the underlying Uloa Formation. In context of this dissertation, King's (1997) hypothesis highlights the interconnectivity between hydrostratigraphic unit 3 (Kosi Bay and Port Dunford Formation) with hydrostratigraphic unit 4 (Uloa Formation). Overall, this interaction can be considered as leaky-confined conditions and is illustrated in

Figure 6-44 where groundwater flows from the western unit of the Port Dunford Formation, through the underlying Uloa Formation and eventually back to the eastern unit of the Port Dunford Formation, (Kelbe and Germishuys, 2010).

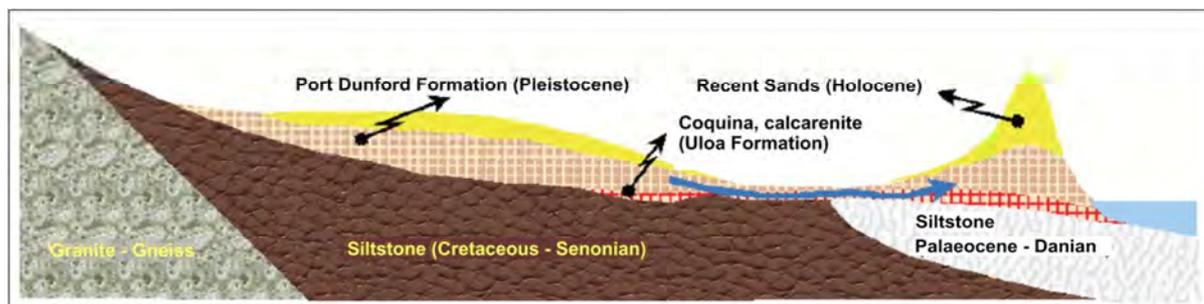


Figure 6-44: Schematic Diagram Displaying the Interaction between the Port Dunford and Uloa Formation, (Kelbe and Germishuys, 2010).

Kelbe and Germishuys (2010) Case Study - 4 which focused on the analyses of storm hydrographs to determine the extent of rainfall to groundwater contribution further emphasised the interconnectivity between the various lithologies. The study revealed that leaky aquifers intercepted at depths of 26 and 36 mbgl (assuming to represent hydrostratigraphic unit 3 and 4, respectively) displayed peak elevations in head after 18 and 47 hours, respectively.

The calcareous nature of the host rock governs the water quality of the Uloa Formation and due to the relatively deep occurrence of the host rock, it is expected that the residence time of the groundwater in the deep aquifer is longer than that of the shallow aquifer, (Schapers, 2011).

Mkhwanazi (2010) analysed several water samples representative of the Uloa Formation and reported that the pH ranged from relatively neutral to slightly alkaline (pH of 6.5 to 7.8). The chemistry of the groundwater samples were dominated by bicarbonate (HCO_3^-) and calcium ions with the calcium-magnesium ratio at 2:1. The enrichment of calcium and carbonate ions was attributed to calcite, shell fragments and coquina which were present in the formations, (Mkhwanazi, 2010).

Hydrogeological Basement of the ZCP (Zululand Group)

Siltstone, conglomerate and sandstone of the Zululand Group represent the deepest water bearing unit in Groundwater Region 65. Hydrogeological data pertaining to the Zululand Group is very limited as the geological formation has an aerial extent of 2.4% (Table 6-8).

Using 13 borehole records, the average borehole depth was at 37.5 mbgl (Table 6-8) and water strike depth was at 25 and 80 mbgl (Figure 6-33). Only two borehole records had water level data of 20 and 30 mbgl (Figure 6-14) and six borehole records contained yield values which were at an average of 0.02 L/s. The aforementioned infers deep, confining aquifer conditions with the siltstone acting as the confining layer, (Worthington, 1978). Due

to the high clay content and strong adhesive forces in the sediments, Meyer *et al.*, (2001) reported that the aquifer had very low permeability.

However, these values are based on very limited data and additional data is required to holistically gauge the hydrogeological properties of the Zululand Group. It must be reiterated that hydrogeological data pertaining to the Zululand Group is extremely limited therefore aquifer parameters derived from literature sources are absent in this discussion.

Several studies such that of Meyer *et al.*, (2001); King (1997) and Mkhwanazi (2010) have reported that the geological formations of the Zululand Group are renowned for yielding saline water. Meyer *et al.*, (2001) reported that groundwater quantity intercepted in the Zululand Group was extremely poor as TDS was reported at >8 000 mg/L.

Interpretation of water quality data from the GRIP dataset indicates that the pH of the Zululand Group ranged from relatively neutral to very alkaline (pH range of 6.5 to 9.05). Electrical conductivity (EC) ranged from 99.7 to 1,113 mS/m of which an average of 416.31 mS/m was calculated. Total dissolved solids (TDS) were significantly elevated and ranged from 598 to 6,678 mg/L with the median TDS concentration at 2,602.39 mg/L. The water quality data derived from the GRIP dataset and King (1997) for the Zululand Group is presented in Table 6-13.

Mkhwanazi (2010) attributed the elevated concentrations of sodium and chloride ions which were at an average concentration of 756.24 mg/L and 1,432.75 mg/L, respectively (Table 6-13) to brine waters in the aquifer or the entrapped clay minerals in the marine deposited formations.

Also evident in Table 6-13 is the high calcium concentration (average of 185.99 mg/L) which is the second highest cation concentration in the dataset. The presence of calcium and carbonate ions was attributed to the mineral calcite and shell fragments present in the geological formations, (Mkhwanazi, 2010).

Based on the discussions above, the Zululand Group was not delineated as a hydrostratigraphic unit. Nevertheless, it is still pertinent to consider the findings of the available data in order to briefly gauge the hydrogeological and geochemical properties of the hydrogeological basement in the study area.

Table 6-13: Partial Groundwater Hydrochemical Data for the Hydrogeological Basement (Zululand Group) in the ZCP (mg/L unless stated otherwise), (GRIP Dataset unless stated otherwise).

Reference	Static Water Level (mbgl)	Borehole Depth (mbgl)	pH (unit)	EC (mS/m)	TDS	Ca	Mg	Na	K	Cl	So ₄
2732AD00008	36.51	46.49	7.44	142.00	946.00	94.90	25.80	156.90	8.30	-	-
2732ADV1166	42.46	46.30	6.50	99.70	598.00	13.00	13.00	170.00	9.50	251.00	32.00
2732ADV1170	38.12	50.00	7.70	110.60	664.00	50.00	19.00	165.00	4.90	194.00	25.00
2832ACR0002	9.50	179.00	7.28	512.00	3,072.00	160.00	45.00	1,000.00	18.00	1,350.00	416.00
2732ABG4727	21.30	37.00	7.18	192.00	1,784.00	167.00	36.00	379.00	6.50	631.00	15.00
2732ADG4725	38.00	64.00	8.15	222.00	1,167.00	19.00	2.00	440.00	1.60	532.00	12.00
2832ACR0001	25.50	186.00	9.05	1,113.00	6,678.00	833.00	1.40	1,900.00	6.00	4,102.00	-
2732CD00142	27.00	240.00	9.04	798.00	5,050.00	151.00	1.00	2,050.00	4.70	2,644.00	610.00
King (1997) ⁸	-	-	6.80	557.50	3,462.50	-	192.80	545.30	35.00	1,758.00	264.50
Average	29.80	106.10	7.68	416.31	2602.39	185.99	37.33	756.24	10.50	1432.75	196.36

⁴ Denotes no data available.

⁸ The water quality presented is an average of the two samples analysed.

6.4 Surface Water – Groundwater Interaction

Surface water – groundwater interaction is principally governed by the position of water level in the surface water body to that of the groundwater table, where the exchange of water occurs both horizontally and vertically. Interaction between surface water and groundwater provides a mechanism of chemical exchange between the various water bodies and influences the chemistry of the ecosystems reliant on these waters, (Parsons, 2004). Sophocleous (2002) reported that the exchange fluxes were a function of the following:

- The distribution and magnitude of hydraulic conductivities within the channel and aquifer media.
- The relationship between the stream stages to the adjacent groundwater table.
- Geometry and position of the stream channel within the alluvial plain.

Variation and distribution of heterogeneous material (accumulation of low permeability sediments in the lake floor) results in slower rates of movement (lower hydraulic conductivities) through the bottom of the lake and therefore the direction of exchange is a function of the hydraulic head, (Sophocleous, 2002; Parsons, 2004). The interaction between the primary aquifer and the adjacent surface water body is shown in Figure 6-45.

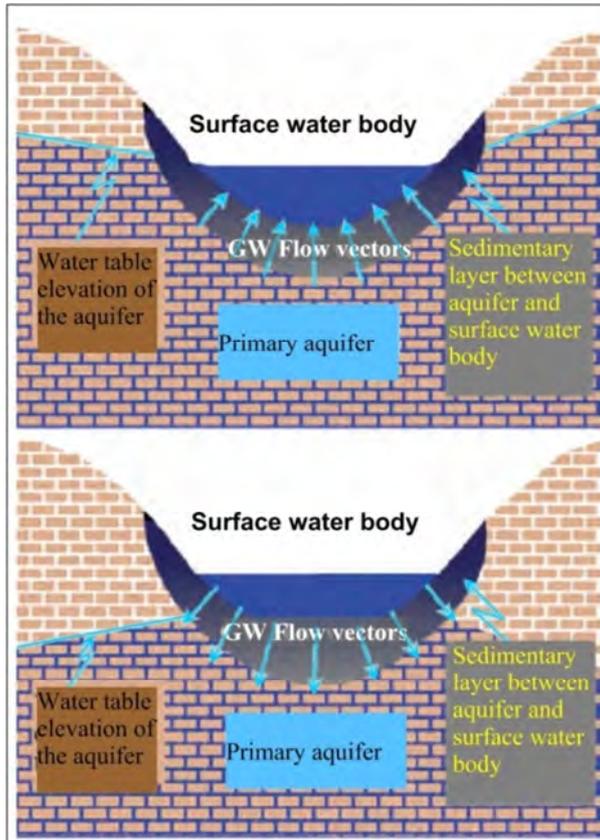


Figure 6-45: Conceptualisation of the Interaction between a Primary Aquifer and a Surface Water Body, (Kelbe and Germishuyse, 2010).

The ZCP is well endowed with several major lakes and therefore there is a strong reliance on the coastal lakes for freshwater supply. These lakes are considered extensions of the primary aquifer and are widely exploited. Persistent baseflow in the smaller feeder streams and direct groundwater seepage along its shoreline demonstrates strong groundwater dependency, (Kelbe and Germishuys, 2010).

Quantification of the level of surface water – groundwater interaction in the study area is presented in Section 6-4.1 while case studies of the level of surface water - groundwater interaction in some of the rivers and lakes in the study area is discussed in the subsequent sections.

6.4.1 Quantification of Surface Water – Groundwater Interaction

Two methods are used to quantify the interaction between surface water and groundwater within the study area. The first is the use of the Herold Curve Fitting Method and the second is the Saturated Volume Fluctuation (SVF), each of which will be briefly discussed below.

The Herold method (Herold, 1980) is one of the common methods used in South Africa to determine the groundwater contribution to flow in a river. The method is based on the total flow in the river being equal to the groundwater contribution and surface runoff. The assumption is then made that all flow below a certain value (called GGMAX) is groundwater flow. The value of GGMAX is adjusted each month according to the surface runoff during the preceding month and is assumed to decay with time.

The SVF method incorporates a lumped parameter approach, taking into account aquifer water levels, abstraction from the aquifer and natural flow. Bredenkamp *et al.*, (1995) applied this method successfully in South Africa. The general equation used to determine recharge is:

$$h_i = h_{i-1} + R_i/S + (I_i - O_i)/SA - Q_o/SA$$

where:

h_i = head at month i (m)

h_{i-1} = head at previous month

R_i = recharge in month i (m)

I_i, O_i & Q_o = inflow, outflow and abstraction in month ' i ' ($m^3/month$)

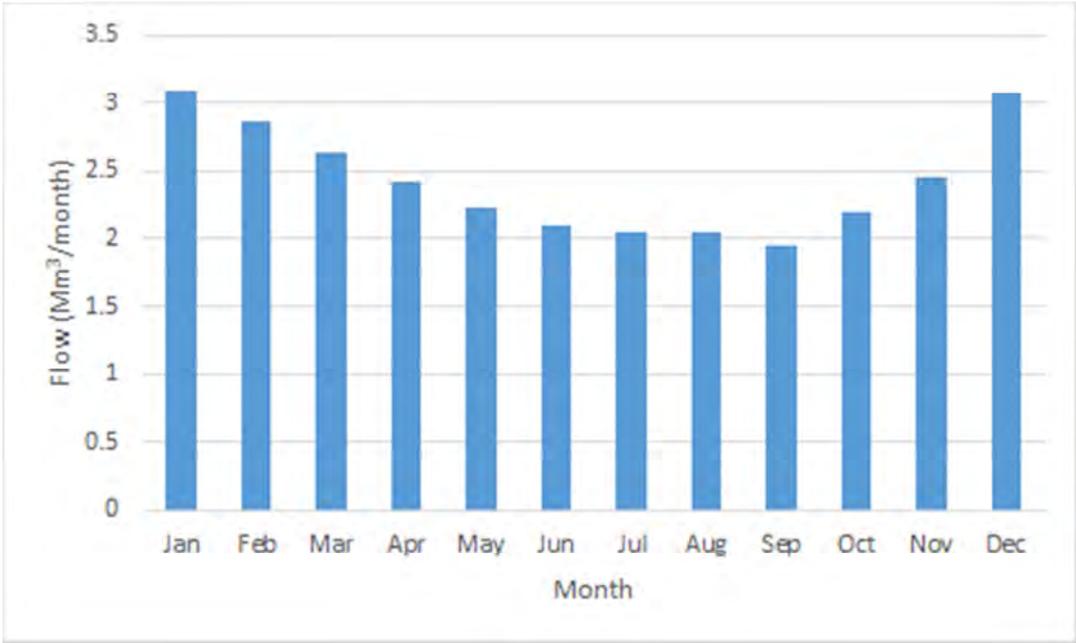
A = area of aquifer (m^2)

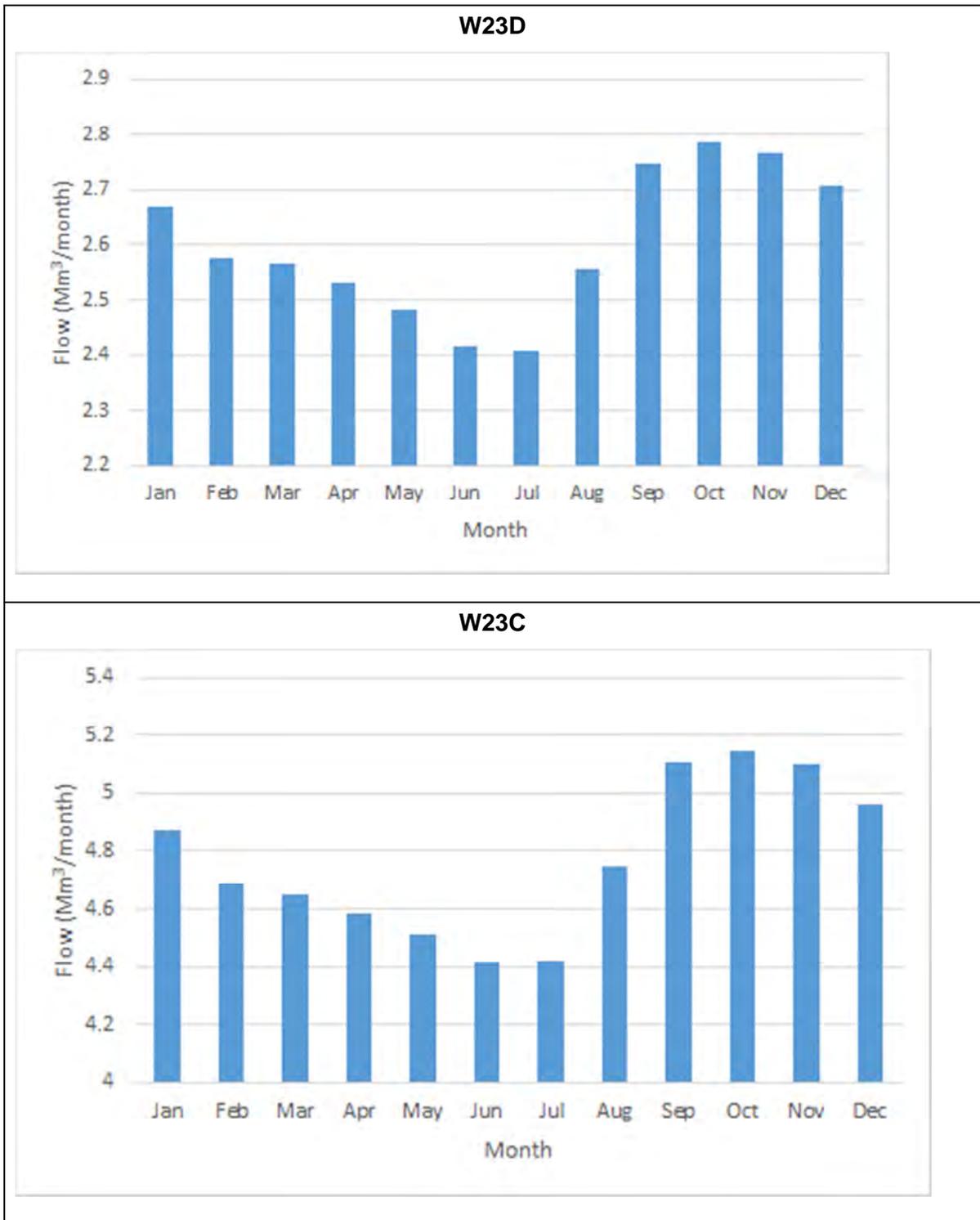
S = specific yield

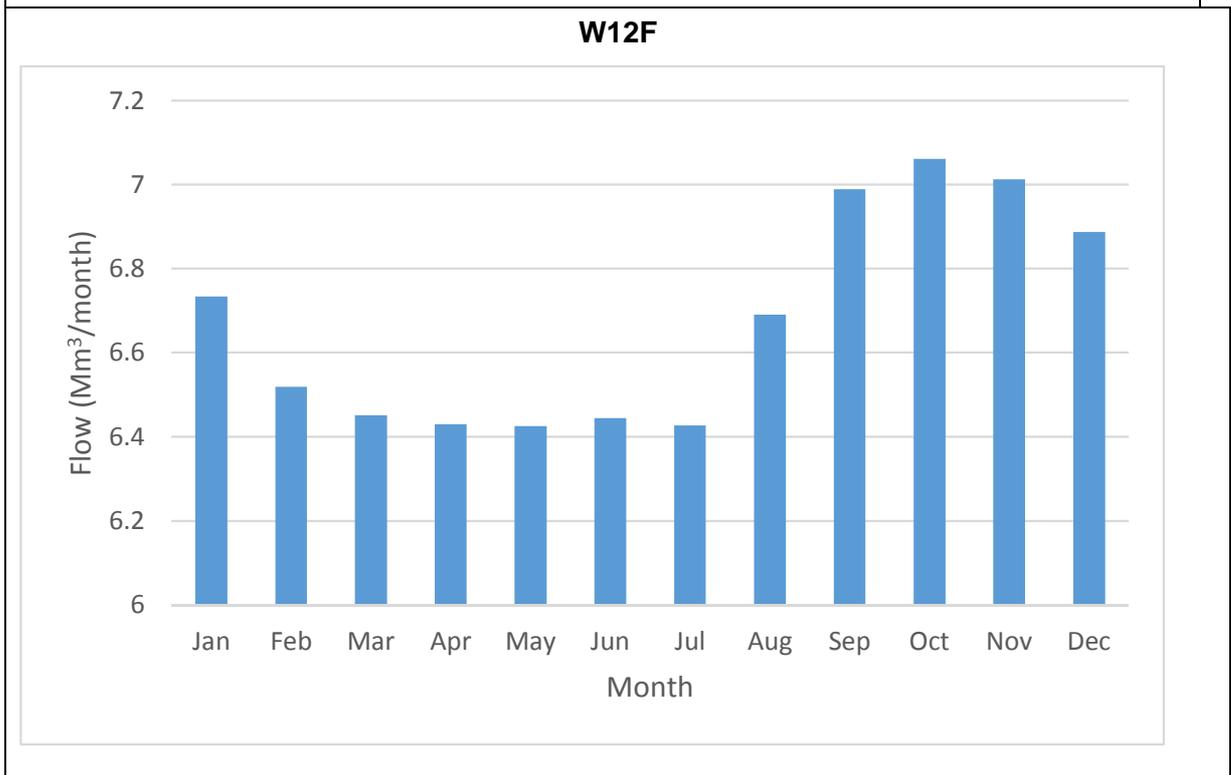
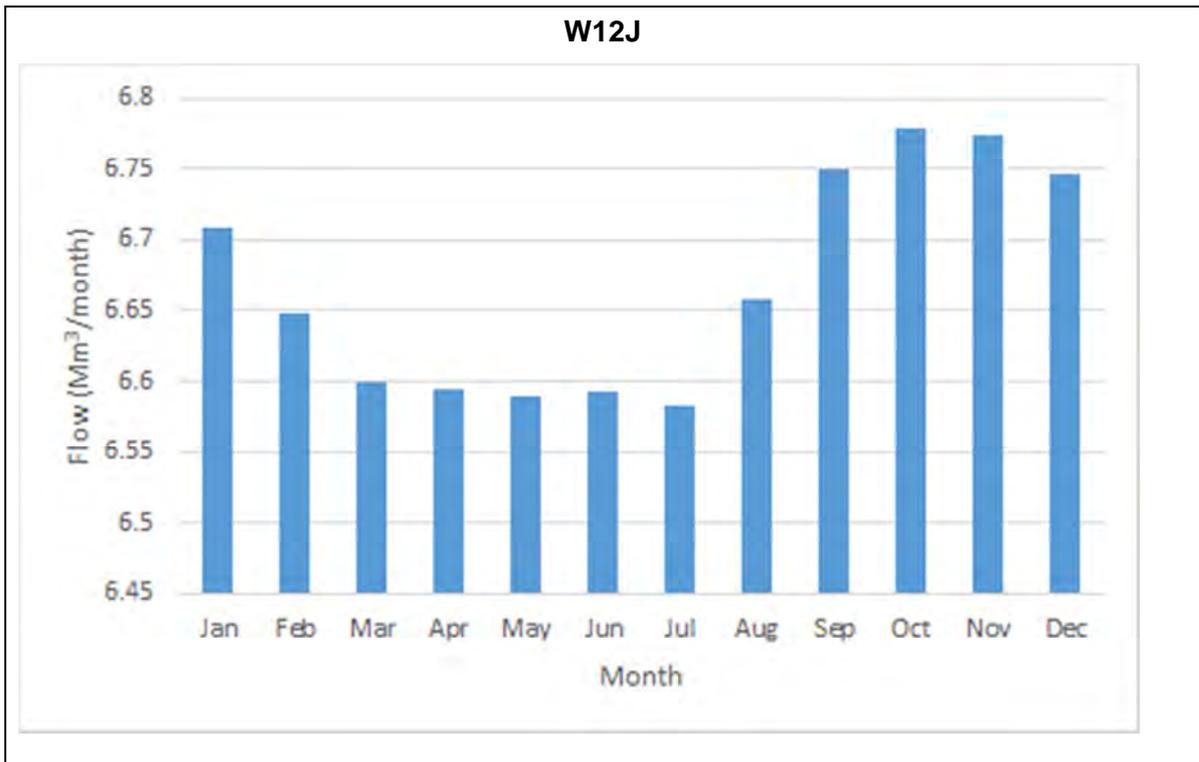
Flow data from the DWA gauges in the study area, where used to determine the surface water (river) - groundwater interaction. A summary of the flow data is provided in Appendix B, (<http://www.dwaf.gov.za/Hydrology>).

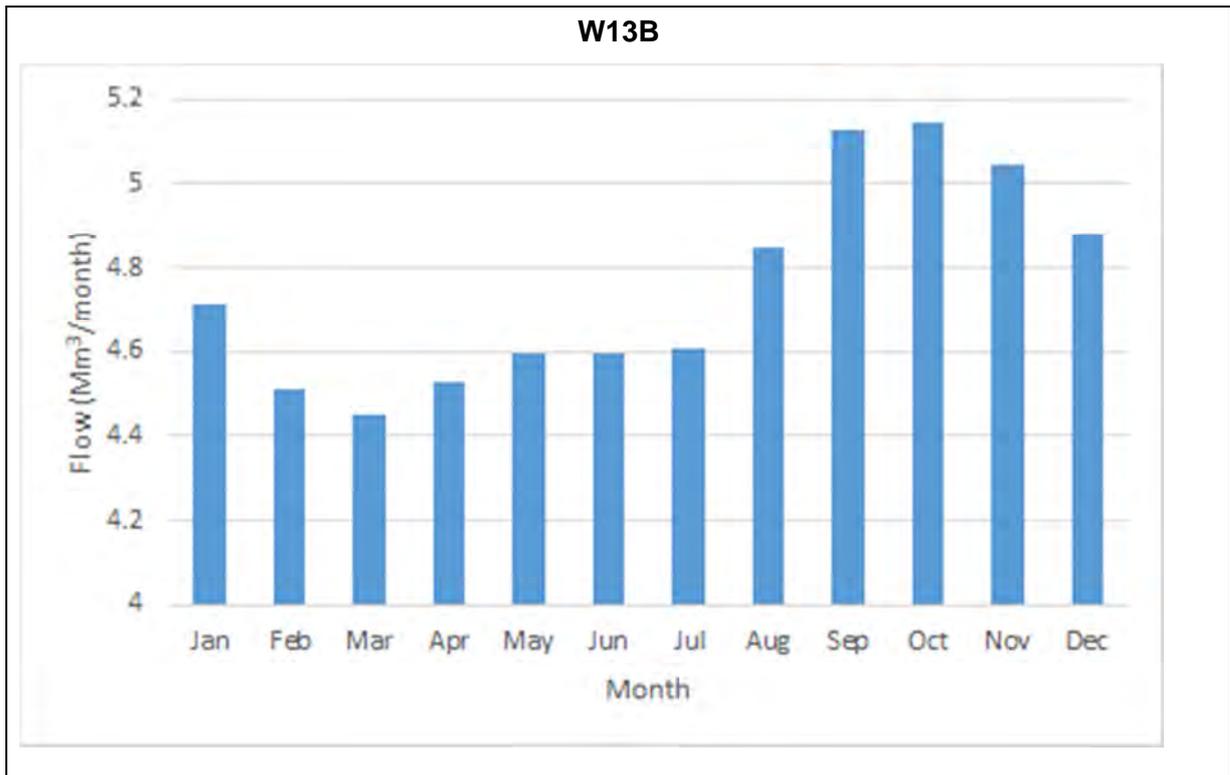
As the flow data in the study area is a concern (Appendix B), the naturalised flow data from WR2005 (WRC, 2005) was used to determine the average monthly groundwater contribution to surface water. Using the aforementioned data, groundwater contribution to surface water bodies in the respective catchments ranged from an average of 2 Mm³/month (W32B catchment) to c.6.6 Mm³/month (W12J catchment). These results are summarised in Table 6-14.

Table 6-14: Groundwater Contribution to Surface Water

W70A																										
No significant rivers in the catchment.																										
<p>W32B</p>  <table border="1"> <caption>Monthly Flow Data for W32B</caption> <thead> <tr> <th>Month</th> <th>Flow (Mm³/month)</th> </tr> </thead> <tbody> <tr><td>Jan</td><td>3.1</td></tr> <tr><td>Feb</td><td>2.8</td></tr> <tr><td>Mar</td><td>2.6</td></tr> <tr><td>Apr</td><td>2.4</td></tr> <tr><td>May</td><td>2.2</td></tr> <tr><td>Jun</td><td>2.1</td></tr> <tr><td>Jul</td><td>2.0</td></tr> <tr><td>Aug</td><td>2.0</td></tr> <tr><td>Sep</td><td>1.9</td></tr> <tr><td>Oct</td><td>2.2</td></tr> <tr><td>Nov</td><td>2.4</td></tr> <tr><td>Dec</td><td>3.1</td></tr> </tbody> </table>	Month	Flow (Mm ³ /month)	Jan	3.1	Feb	2.8	Mar	2.6	Apr	2.4	May	2.2	Jun	2.1	Jul	2.0	Aug	2.0	Sep	1.9	Oct	2.2	Nov	2.4	Dec	3.1
Month	Flow (Mm ³ /month)																									
Jan	3.1																									
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Oct	2.2																									
Nov	2.4																									
Dec	3.1																									
W32H																										
Catchment is dominated by groundwater flow towards Lake St Lucia.																										

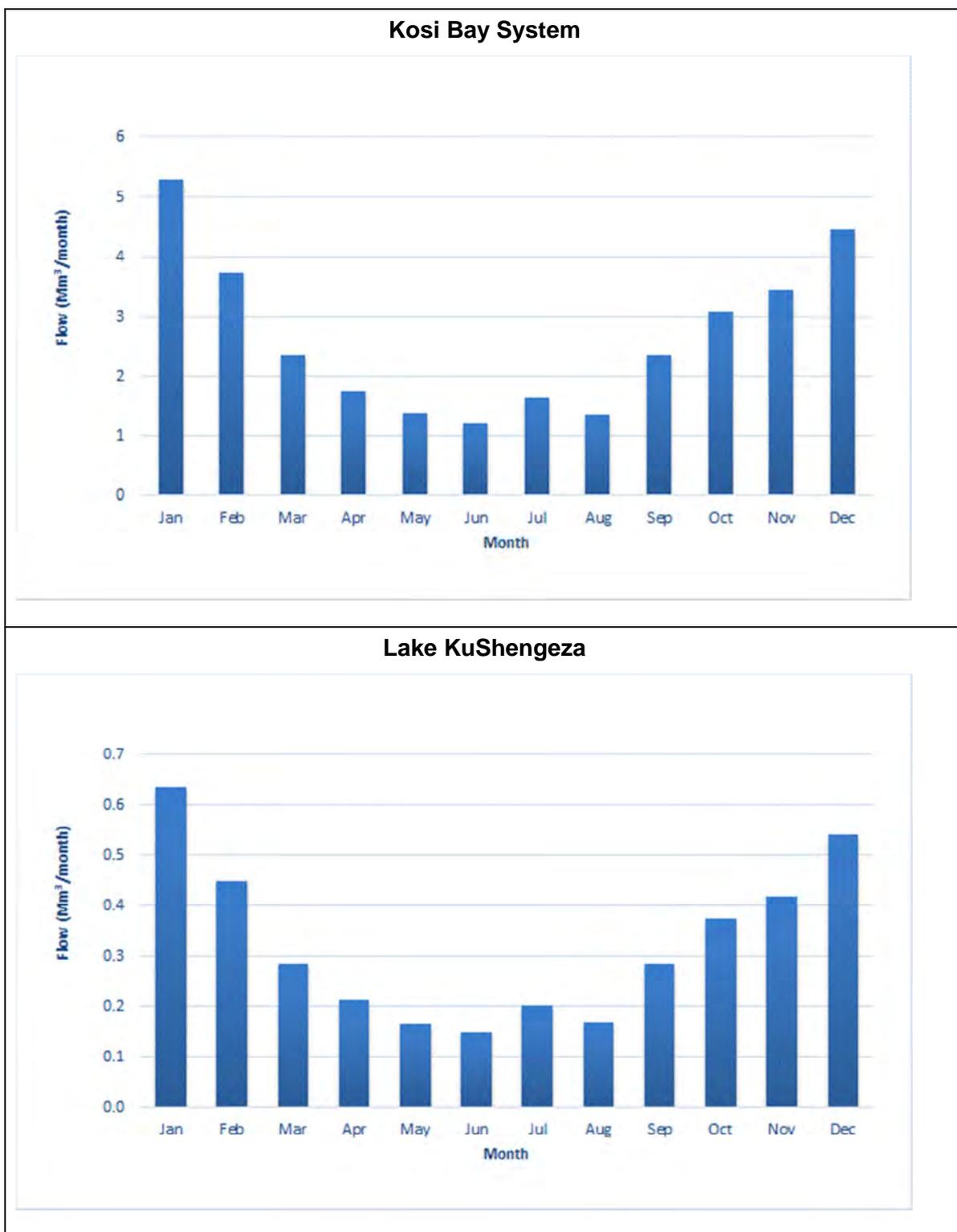


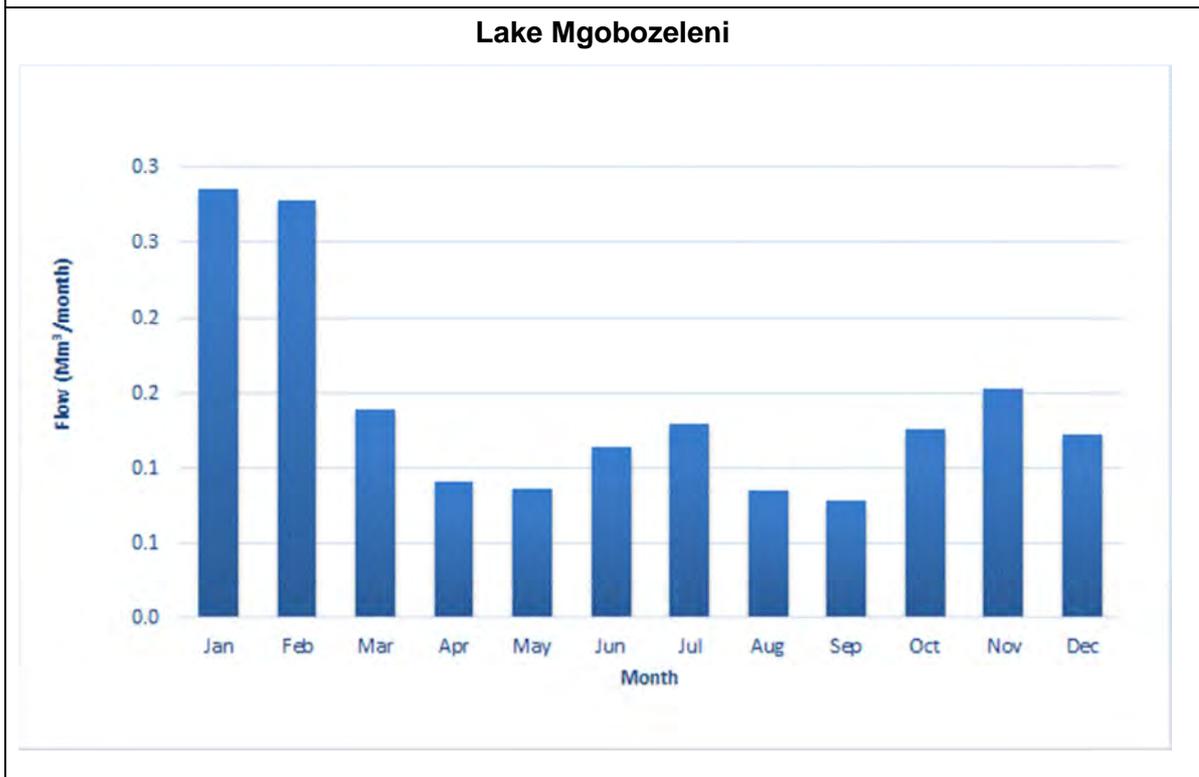
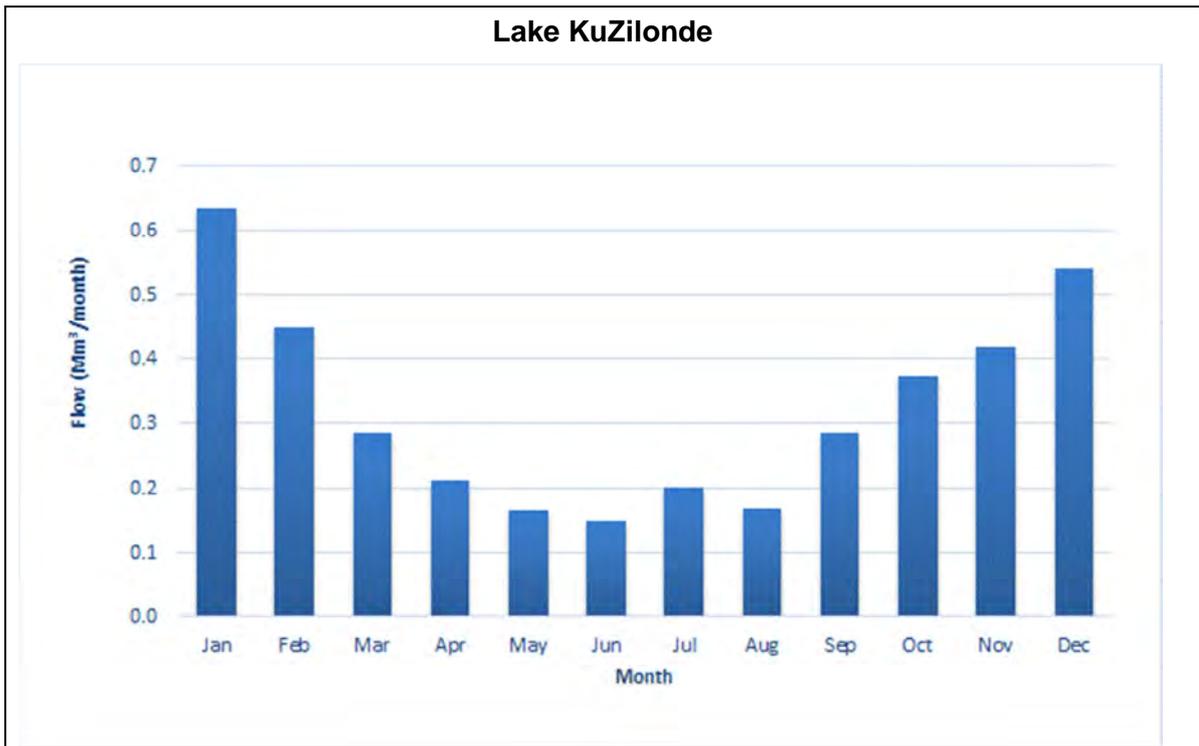


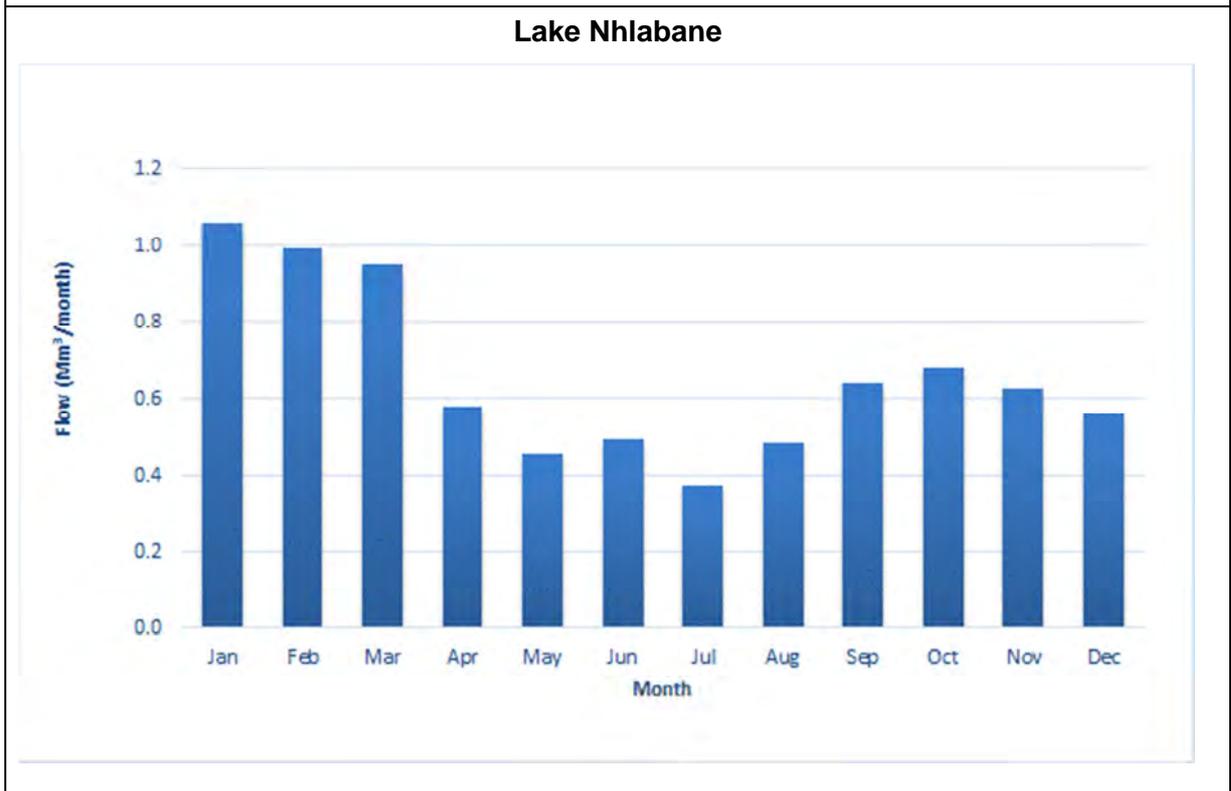
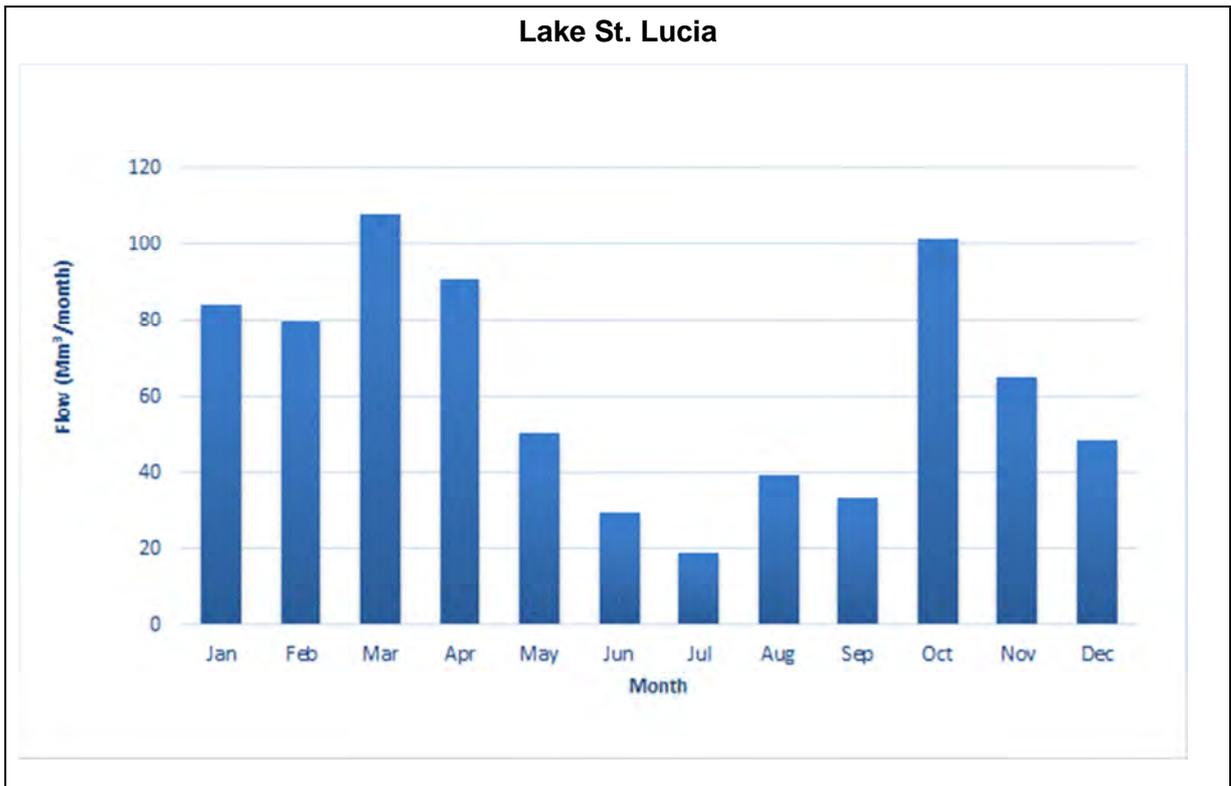


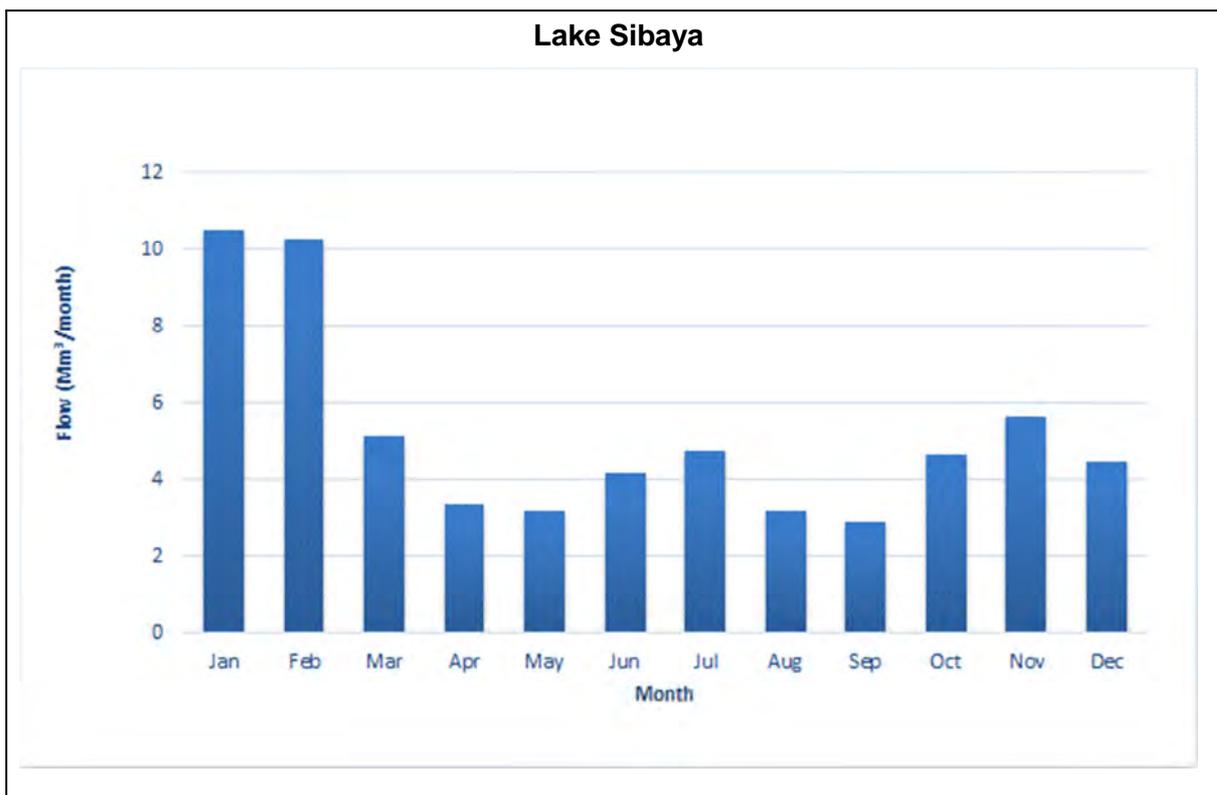
The interaction between groundwater and the lakes in the study area was calculated using the SVF method, assuming that the specific yield was at 0.02 and the recharge at 10% of the MAP. The results indicate the groundwater contribution to the lakes ranged from an average of 0.1 Mm³/month (Lake Mgobozeleni) to c.60 Mm³/month (Lake St. Lucia) and is shown in Table 6-15.

Table 6-15: Average Monthly Groundwater Contribution to Lakes in the ZCP using the Saturated Flow Volume Method.









6.4.2 Interaction of Rivers with Groundwater

According to Winter *et al.*, (1998), the interaction between streams and groundwater is prevalent in all terrain types of which their interaction is categorised in the three ways which is summarised below. Streams gain water from the inflow of groundwater via the stream bed. This will occur when the altitude of the water table in the vicinity of the stream is higher than the altitude of the stream-water surface.

- Streams lose water to the underlying aquifer via outflow through the stream bed when the water table in the vicinity of the stream is lower than the altitude of the stream-water surface.
- Streams do both in that they are recharged by groundwater in some reaches and lose water in other reaches of the river.

The interaction of rivers with groundwater is also advocated using case studies presented below:

Mseleni River

Investigations undertaken by Weitz and Demlie (2013) indicated that samples collected from the Mseleni River, were isotopically deficient. The chemistry of the surface water samples was similar to that of the surrounding groundwater i.e. depleted in isotopes on account of direct recharge from precipitation as rainfall in the vicinity of Lake Sibaya was typically depleted in $\delta^{18}\text{O}$ and δD).

Based on the above, it is possible that the underlying aquifer recharges the river therefore the Mseleni River can be regarded as a gaining stream, (Weitz and Demlie, 2013). The relationship discussed above, highlights the dynamic nature of the shallow aquifer and surface water body where dependency on groundwater recharge to sustain flow regimes is evident.

Nkazana Stream

According to Kelbe and Germishuys (2010), the Nkazana Stream has always been flowing even in periods of drought, as experienced in 2002. Based on the above, it appears that the Nkazana Stream can be regarded as a gaining stream as the underlying shallow aquifer recharges the stream even in periods of drought, (Kelbe and Germishuys, 2010).

6.4.3 Wetland Distribution

According to Section 6-3.1, the reduced permeability and hydraulic conductivity in the Kwabonambi, Kosi Bay and Port Dunford Formation give rise to wetlands which are often characterised by a perched water table, (Jeffares and Green, 2012). The erratic distributed aforementioned geological formations govern the occurrence of wetlands which are marked by the occurrence of hygrophilous coastal grasslands and swamps, (Tinley and Van Riet, 1981).

Grundling *et al.*, (2013) assessed the distribution of wetlands over periods of water surplus and droughts. Using a combination of Landsat TM and ETM imagery, the study identified permanent groundwater fed wetland systems during dry periods in contrast to the combination of permanent and temporary wetlands identified during the wet periods. The comparison further revealed that dry periods resulted in an 11% decrease in the distribution of wetlands which corresponded to a gradual increase (7%) in grassland. It is important to note that some areas which appeared to be grassland were actually wetlands.

6.4.4 Interaction between Lakes and Groundwater

The shallow aquifer in the study area plays an integral role in sustaining various functions of surface water bodies. At Lake St. Lucia, groundwater is vital in the establishment of refugia sites during hyper saline conditions whereas at Lake Sibaya, the freshwater system is regarded as an extension of the regional groundwater table under natural conditions. In comparison to Lake Sibaya, groundwater represents a very constant yet minute contribution to the Lake St. Lucia's water balance whereas, barring precipitation, groundwater is the main source of recharge to Lake Sibaya and is crucial in sustaining lake levels. With regards to Kosi Bay, several lakes define the Kosi Bay system with inflow being derived from marine sources and groundwater, (Kelbe and Germishuys, 2010).

The aforementioned highlights the inter-connection and level of groundwater dependency between the shallow aquifer and the surrounding lakes however, one must be cognisant that the degree of dependency for the respective lakes is unique and highly variable, (Kelbe and Germishuys, 2010).

The role of groundwater and the level of dependency of the various lakes in the study area are discussed below:

Lake St. Lucia

Lake St. Lucia is situated at the southern extremity of the Maputaland Coastal Plain and is the largest estuarine system in Africa, encompassing an area of c.36,000 ha. The water balance for the lake comprises 45% contribution from surface hydrology and 50% from direct precipitation. Therefore, groundwater contribution to the lake is consistent but low. However, during prolonged periods of drought; groundwater serves as the only source of replenishment for the lake. The dominant source of fresh water seepage arises from the groundwater mound of the Embomveni Dune Ridge situated in the Eastern Shore areas while other seepage zones along the 187 km shoreline supplement the fresh water source, (Wright *et al.*, 2000).

The Embomveni Dune Ridge and surrounding undulating dune cordons creates a distinct groundwater mound which has a radial groundwater flow pattern, (Taylor *et al.*, 2006). The Embomveni Dune Ridge is a constant supply of groundwater and groundwater level monitoring has indicated that the water level in the groundwater mound has seldom varied by more than 3 m, (Kelbe and Germishuys, 2010).

Groundwater seepage along the Eastern Shores occurs where the dune cordon is in close proximity to the estuary shore. The eastern shores of St. Lucia Estuary are capped by nodular ferricrete deposits. These deposits suggest long term groundwater discharge along the shoreline and are likely to be associated with the Kosi Bay dune landscape. In addition, the groundwater confluence along the shoreline is demarcated by clayey formations and estuary associated vegetation which can only thrive in a mixture of diluted saline and fresh water, (Taylor *et al.*, 2006).

Groundwater seepage from the western shoreline to the southern half of False Bay under natural conditions contributed an average of 22,000 m³/d where c.17,000 m³/d discharged into the southern lakes and almost 5,000 m³/d discharged into the estuary, (Kelbe and Germishuys, 2010). These values are higher than the calculated groundwater contribution to lakes presented in Table 6-15.

Analyses of groundwater samples collected from the seepage zones indicate the presence of two distinct chemical signatures i.e. Ca - HCO³ enrichment which is attributed to the solution of calcium carbonate in the calcarenite and Na - Cl dominated which is associated

with precipitation. The low EC of the groundwater discharging into the estuary (Figure 6-46 (a)) is at the same concentration to that of the EC measured in the groundwater monitoring wells installed around the lake. The EC signature emphasises ion depletion. The ion deficient chemistry is constant during both wet and dry seasons thus confirming the sustained groundwater inflow to the lake, (Taylor *et al.*, 2006).

During the period of severe drought experienced from 2003 to 2005, the lake level dropped and exposed the shoreline of Lake St. Lucia showing the zones of groundwater seepage (Figure 6-46 (b)) which had EC values of <5 mS/m in comparison to the EC of the lake which was at >40 mS/m, (Kelbe and Germishuys, 2010).

Chemical analyses of groundwater seepage along the lake's shoreline also confirmed the presence of groundwater dependant habitats referred to as the link between terrestrial and estuarine environments. Groundwater plays a critical role in sustaining various species and ecosystems especially in periods of drought where the sea water inflow coupled with high evaporation rates leads to hyper saline waters in the lake.

Under salinity stress, the survival of species (animals and vegetation) occurs where salinity levels are lower than that of the adjacent estuary and therefore the microhabitats are widespread, (Taylor *et al.*, 2006). Localised groundwater seepage meets the above criteria (very low salinity) therefore ecological biodiversity is preserved by the constant flux of groundwater seepage which allows for the development of refugia sites along the shorelines during periods of drought, (Clulow *et al.*, 2012).

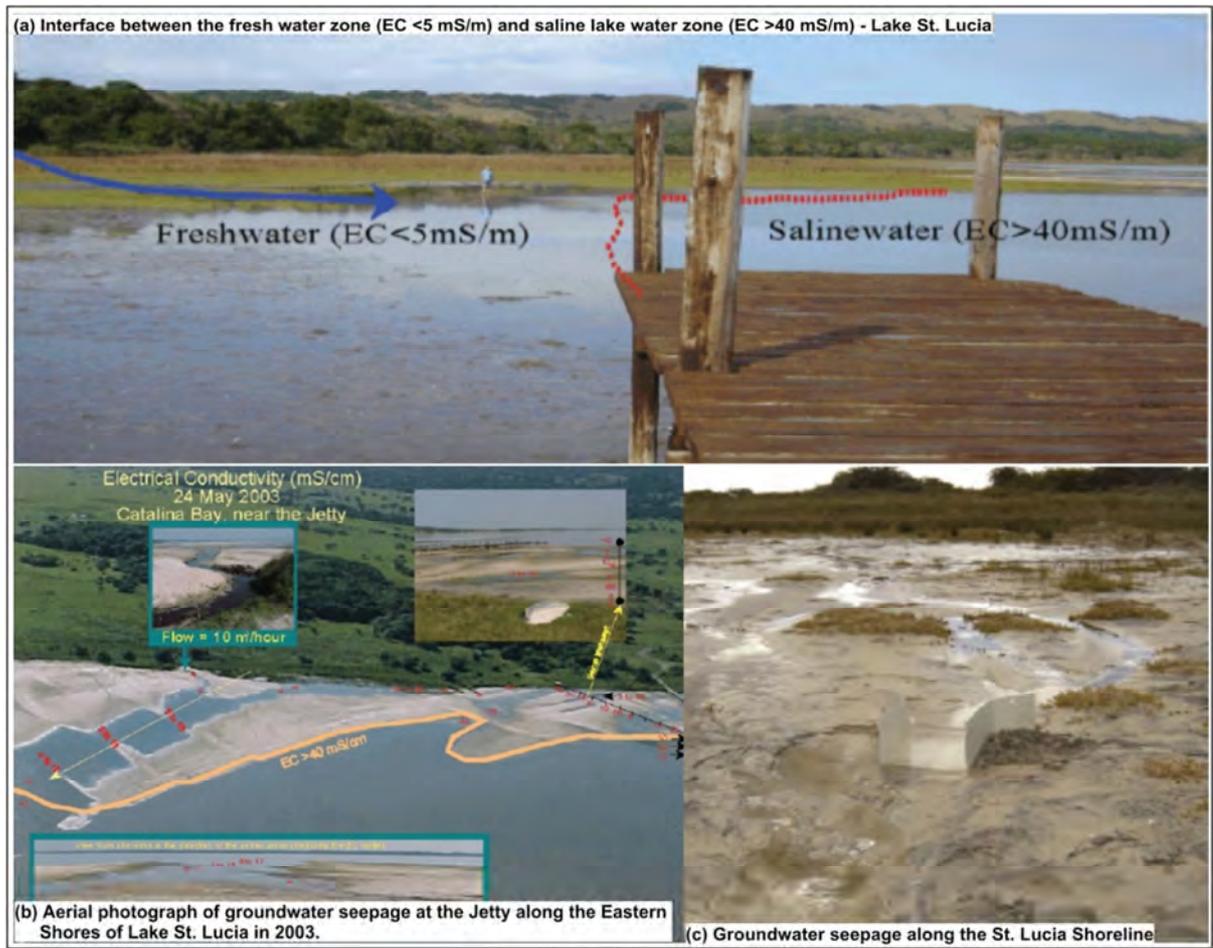


Figure 6-46: Groundwater Seepage along the Shoreline of Lake St. Lucia, (Kelbe and Germishuys, 2010).

Lake Mzingazi

Worthington (1978) discussed the potentiometric surfaces of Lake Mzingazi and of importance, the pronounced zones of depression around major streams such that of the Mdibi River situated along the northern end of Lake Mzingazi. These extended depressions confirmed that the feeder streams of the Mzingazi catchment was consistently being recharged by the groundwater system.

Groundwater seepage around the perimeter of Lake Mzingazi was calculated at 5,875 m³/d while groundwater seepage loss manifested in the shallow, fine sands (hydrostratigraphic unit 1*⁹) and was restricted to areas in which the Upper Pleistocene (hydrostratigraphic unit 2*), Middle Pleistocene (hydrostratigraphic unit 3*) and the Micoene (hydrostratigraphic unit 4*) were absent. Thus, groundwater seepage loss along the perimeter of Lake Mzingazi was calculated at 1,350 m³/d. Baseflow across Lake Mzingazi was estimated at

⁹ (*) Refers to the vertically delineated hydrostratigraphic units.

80 000 m³/d and emphasizes the strong source of replenishment for Lake Mzingazi during periods of drought, (Worthington, 1978).

Analyses of data collected from a network of nested piezometers installed around Lake Mzingazi have revealed that a large proportion of the water budget for Lake Mzingazi arises from groundwater seepage. The nested piezometers which monitor the groundwater levels in the various aquifers, suggested that the source of groundwater seepage into Lake Mzingazi, which occurs along the shoreline, arises from the deeper lithostratigraphic units such as the Uloa Formation, (Kelbe and Germishuys, 2000).

Lake Sibaya

According to Wright *et al.*, (2000), Lake Sibaya is a freshwater lake. Recharge to Lake Sibaya occurs via groundwater seepage, rainfall and small streams. The lake is characterised by constantly fluctuating water levels which can be attributed to erratic groundwater recharge, evaporation and seepage loss from the dunes.

Meyer *et al.*, (2001) utilised stable isotope analyses to determine groundwater leakage to the ocean. According to the findings of the study, fresh water seepage was observed along Gobeys Point which is situated opposite the southern end of Lake Sibaya.

Isotope analysis of a sample of the seepage indicated that $\delta^{18}\text{O}$ concentration equated to +1.85% of the Standard Mean Ocean Water (SMOW). When compared to the surface water chemistry of Lake Sibaya ($\delta^{18}\text{O} = +2.2\%$), local sea water ($\delta^{18}\text{O} = +0.6\%$) and groundwater around the lake ($\delta^{18}\text{O} = -4$ to -2%), it was apparent that the fresh water seepage sample was representative of a mixture of water from Lake Sibaya and sea water. Groundwater was not considered as a potential source as $\delta^{18}\text{O}$ concentrations were lower than that of the remaining concentrations discussed above.

Weitz and Demlie (2013) reported that groundwater samples collected seawards of Lake Sibaya, along the coastal dune cordon, displayed isotopic signature's representative of the both the lake and groundwater. The mixed isotopic signature confirms the movement of lake water through and below the coastal dune cordon to the ocean and conforms to the findings documented by Meyer *et al.*, (2001).

Lake Cubhu

Analyses of the water balance for Lake Cubhu indicates that inflow into the lake as groundwater seepage along its shoreline amounts to 14,000 m³/d in comparison to the inflow derived from rivers (out of the aquifer via the rivers) which is estimated at 20,000 m³/d. This highlights Lake Cubhu's strong groundwater dependency. However, there is groundwater outflow to the Mhlatuze estuary, (Kelbe and Germishuys, 2010).

7 Anthropogenic Impacts

“Anthropogenic impacts, processes or materials are those that are derived from human activities as opposed to those occurring in natural environments without human influences”, (<http://www.eea.europa.eu>).

According to Campbell *et al.*, (1992), unconfined aquifers are extremely vulnerable to pollution as they are composed of highly transmissive deposits with an absence of an overlying impenetrable protecting layer. This suggests that the aquifer has very little attenuating capacity.

The term ‘vulnerability’ can be defined as ‘the intrinsic properties of the strata separating a saturated aquifer from the land surface which determines the sensitivity of that aquifer to being adversely affected by pollution loads applied at the surface’ (Schmoll *et al.*, 2006). According to Sililo *et al.*, (2001), the vulnerability of an aquifer to pollution is a function of the following:

- The time associated with the travel of the infiltrating water and pollutants.
- The quantity of pollutants that intercept the groundwater table.
- The attenuation capacity of the geological media through which the pollutant and groundwater has migrated through.

However, the aforementioned are also influenced by the following geological and hydrogeological characteristics of an area, (Sililo *et al.*, 2001):

- Type of soils that overlie the groundwater table.
- Type of pollutant discharge i.e. point (single identifiable source of pollution) or diffuse sources (inputs and impacts which occur over a wide area and are not easily attributed to a single pollutant source).
- The thickness of the unsaturated zone through which the pollutant travels.

In addition, Meyer *et al.*, (2001) listed the following hydrogeological properties of an aquifer which could influence pollution in the subsurface environment:

- Rapid dispersion of pollutants is likely to occur in highly transmissive deposits.
- The progression of a pollution plume is a function of the hydraulic gradient.
- The significance of the source of pollution tapers from discharge sources in the groundwater environment.

The impact of groundwater pollution is influenced by the geological medium in which the pollutant migrates through. Pollution attenuation in the soil and unsaturated zone are affected by physical (dispersion, filtration and gas movement), chemical (adsorption, dissolution, oxidation-reduction and acid-base reactions) and biological (decay, respiration

and cell synthesis) processes which has the ability to attenuate pollutants. A prolonged period of contact between the pollutant and soil media enhances the decay and sorption process which is referred to as natural attenuation, (Sililo *et al.*, 2001).

An increase in the moisture content of the unsaturated zone may increase the vulnerability of the aquifer via the presence of rapid migration pathways which limits the potential for attenuation by mobilising adsorbed pollutants. Shallow groundwater (<5 mbgl) is assumed to be at the highest probability of pollution regardless of the lithology of the unsaturated zone. Furthermore, the attenuation capacity of the unsaturated zone increases with an increase in the groundwater table. In the saturated zone, the dominant pollutant transport mechanisms are advection, dispersion and molecular diffusion, (Usher *et al.*, 2004). The transport of pollutants in the subsurface environment is shown in Figure 7-1.

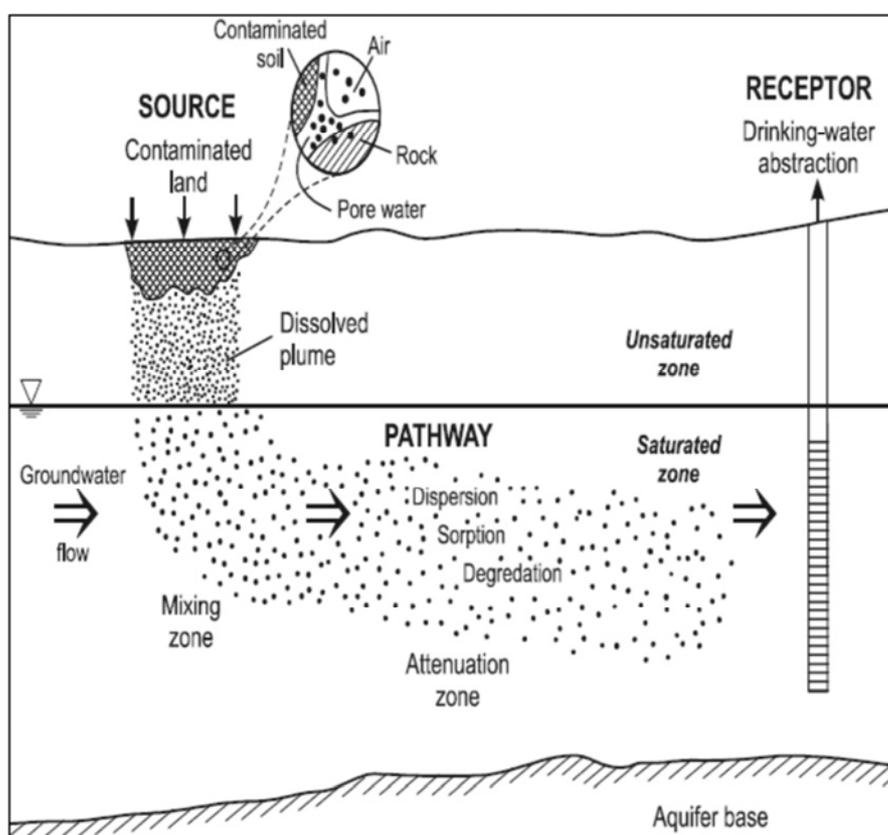


Figure 7-1: Pollutant Transport Model, (Schmoll *et al.*, 2006).

Meyer *et al.*, (2001) study revealed that shallow groundwater levels were responsible for sustaining several sensitive and complex ecosystems thus emphasising that anthropogenic impacts such as mining, afforestation, agriculture and the establishment of rural settlements would have adverse effects.

Similar sentiments were reiterated by Kelbe and Germishuys (2010) as several case studies revealed strong groundwater dependency and interaction between surface water

bodies and the underlying aquifer. Therefore, potential pollution entering the subsurface environment would have a profound and widespread effect on the aquifer and its receiving hydrological and ecological environments.

Based on the above, the ZCP can be regarded as very sensitive. A geohydrology sensitivity map is shown in Figure 7-2 and correlates with the area that Vegter (2001) referred to as Groundwater Region 65.

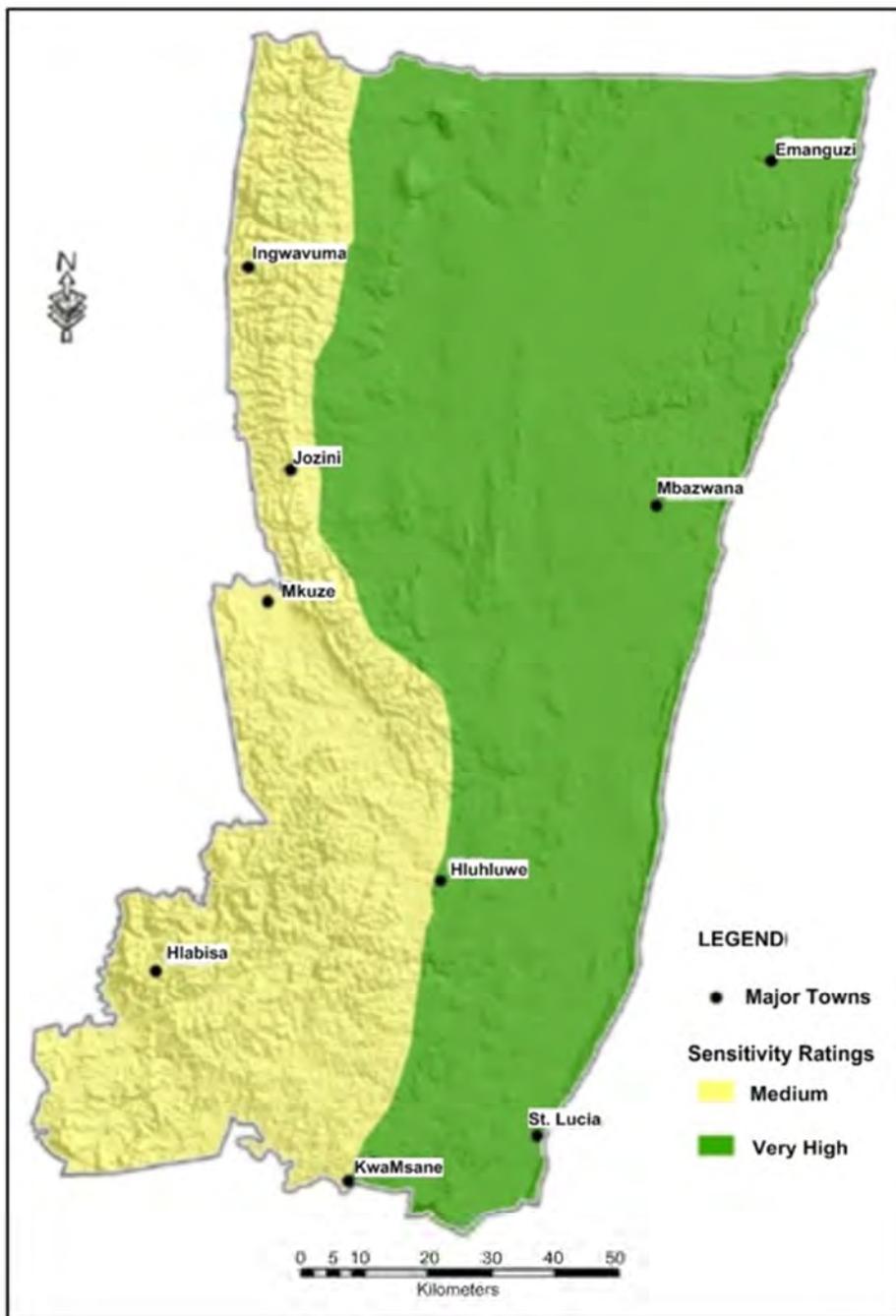


Figure 7-2: Geohydrology Sensitivity Map, (UKDM, 2012).

The main sources of groundwater pollution and their characteristics are presented in Table 7-1. It must be noted that the pollution sources and impacts associated with the municipal pollution category is directly affiliated with urban land use.

Table 7-1: Main Sources of Groundwater Pollution with Some of Their Main Characteristics, (Sililo *et al.*, 2001).

Pollution Category	Pollution Source	Main Pollutant	Potential Impact
Municipal	Sewer leakage.	Nitrate, viruses and bacteria.	Health risk to users, eutrophication of water bodies, odour and taste.
	Septic tanks, cesspools and privies.	Nitrate, minerals, organic compounds, viruses and bacteria.	
	Sewage effluent and sludge.		
	Storm water runoff.	Bacteria and viruses.	
	Landfill sites.	Inorganic minerals, organic compounds, heavy metals, bacteria and viruses.	
	Cemeteries.	Nitrates, bacteria and viruses.	Health risk to water users.
Agriculture	Feedlot wastes.	Nitrate-nitrogen-ammonia, viruses and bacteria.	Health risk to water users.
	Pesticides and herbicides.	Organic compounds.	Toxic or carcinogenic.
	Fertilisers.	Nitrogen and phosphorous.	Eutrophication of water bodies.
	Leached salts.	Dissolved salts.	Increased TDS in groundwater.
Industrial	Process waster and plant effluent.	Organic compounds and heavy metals.	Carcinogens and toxic elements (As and Cn).
	Industrial landfill sites.	Inorganic minerals, organic compounds, heavy metals, bacteria and viruses.	Health risk to users, eutrophication of water bodies, odour and taste.
	Leaking storage tanks (e.g. petrol stations).	Hydrocarbons and heavy metals.	Odour and taste.
	Chemical transport.	Hydrocarbons and chemicals.	Carcinogens and toxic compounds.
	Pipeline leaks.		
Atmospheric deposition	Coal fired power stations.	Acidic precipitation.	Acidification of groundwater and toxic leached heavy metals.
	Vehicle emissions.		
Mining	Mine tailings and stockpiles.	Acid drainage.	May increase concentrations of some compounds to toxic levels.
	Dewatering and mine shafts.	Salinity, inorganic compounds and metals.	
Groundwater Development	Salt water intrusion.	Inorganic minerals and dissolved salts.	Steady water quality deterioration.

7.1 Delineation of Anthropogenic Impacts

The delineation of anthropogenic activities is required to gauge the level of impact on both a regional and local scale and also to discuss its occurrence and impact on the underlying hydrogeological environment. Using the methodology adopted in Section 4-4, anthropogenic activities were delineated on the basis of land use for the eight quaternary catchments which this dissertation focuses on. The dominant land use per quaternary catchment and associated anthropogenic activity is presented in Table 7-2 and shown in Figure 7-3. An enlarged image of the legend for Figure 7-3 is shown as Plate 7-1.

Table 7-2: Dominant Land Use per Quaternary Catchment and Associated Anthropogenic Activity

Quaternary Catchment	Dominant Land Use	Associated Activity	Anthropogenic
W12F	1. Sugar cane - commercial	Agriculture	
	2. Plantation - both existing and felled.	Forestry	
	3. Rehabilitated mines - high vegetation.	Mining	
	4. Built up - dense settlement	Urban / Industrial Land Use	
W12J	1. Plantation - both existing and felled.	Forestry	
	2. Mining.	Mining	
	3. Built up - dense settlement.	Urban / Industrial Land Use	
W13B	1. Plantation - both existing and felled.	Forestry	
W23C and W23D	1. Plantation - both existing and felled.	Forestry	
	2. Forests.	Forestry (natural)	
	3. Sugar cane – commercial.	Agriculture	
	4. Wetlands.	Surrounding land use has the potential to impact sensitive environmental receptors.	
W32B and W70A	1. Bare sand.	None	
	2. Wetlands.	Surrounding land use has the potential to impact sensitive environmental receptors.	
	3. Plantations both existing and felled.	Forestry	
	4. Rural – subsistence.	Rural practises.	
W32H	1. Plantation - both existing and felled.	Forestry	
	2. Forests.	Forestry (natural).	
	3. Wetlands.	Surrounding land use has the potential to impact sensitive environmental receptors.	

Note: The land use is listed in a sequential manner where '1' represents the dominant land use.

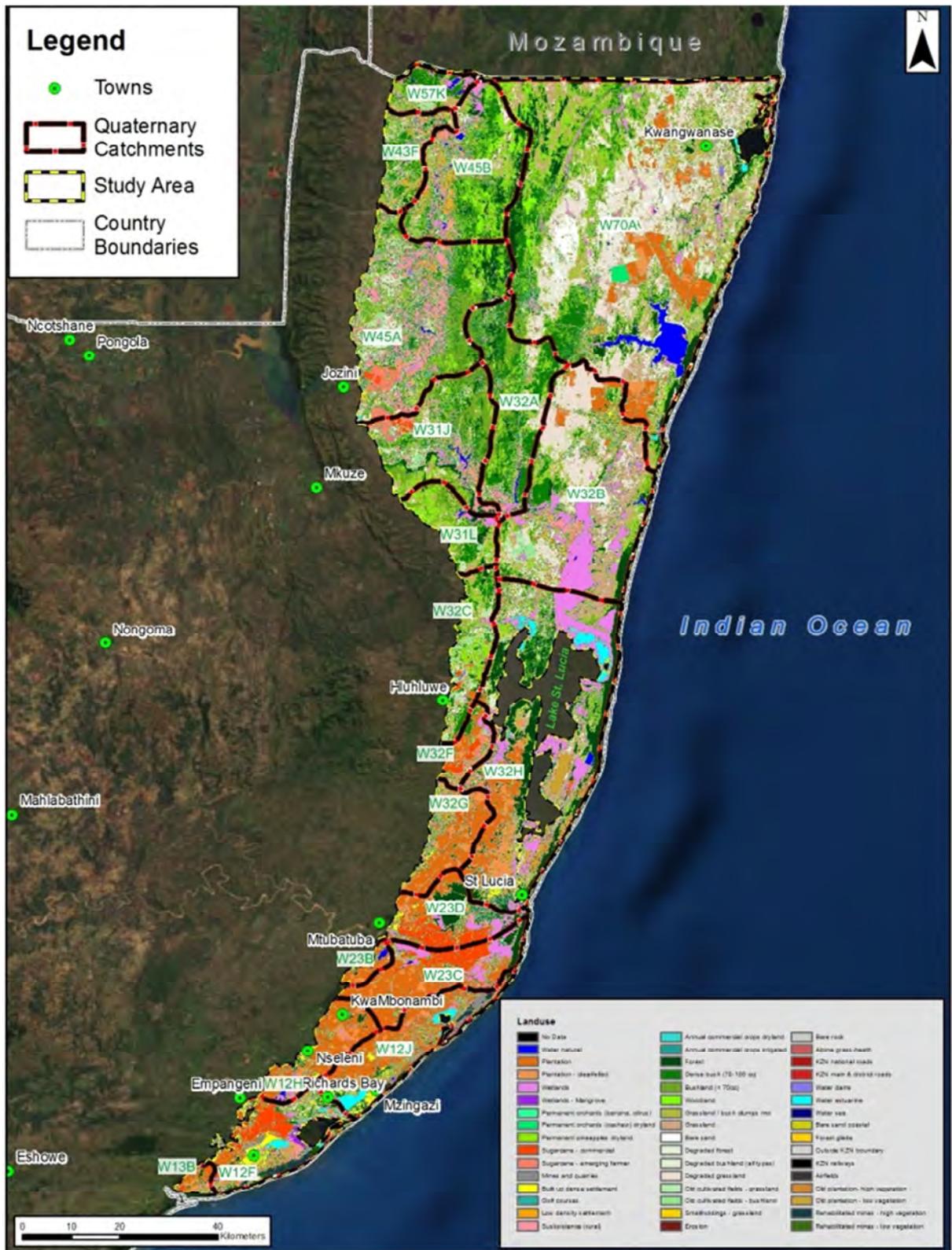


Figure 7-3: Land Use Map for the ZCP and Surrounds, (Ezemvelo, 2011).



Plate 7-1: Enlarged Image of the Legend Shown in Figure 7-3, (Ezemvelo, 2011).

Based on the delineation of anthropogenic activities (Table 7-2 and Figure 7-3), it appears that Lake St. Lucia acts as a physical boundary in the delineation of anthropogenic activities on account of quaternary catchments situated relatively south of Lake St. Lucia (W12F, W12J, W13B, W23C, W23D and W32H) being predominantly characterised by anthropogenic activities pertaining to commercial forestry (existing and felled plantations) and agriculture (sugar cane farming). Despite the broad categorisation, a key concern is the presence of several wetlands and surface water bodies and its associated ecological environments which are likely to be impacted by the surrounding anthropogenic activities.

In contrast, quaternary catchments W70A and W32B situated relatively north - northwest of Lake St. Lucia are predominantly characterised by either barren (bare sand) or vegetated land (woodlands and bushlands) interspersed with commercial sugar cane farming, forestry and rural practises (subsistence land use and farming) which are localised. However, similar to the quaternary catchments situated relatively south of Lake St. Lucia, expansive wetlands and several surface water bodies are also present.

7.2 Types of Anthropogenic Activities and its Associated Impacts

Based on the discussions above (Section 7-1), a detailed examination of the various anthropogenic activities and its impacts to the hydrogeological and associated environments are presented in the subsequent section along with relevant case studies. However, one must be cognisant that anthropogenic activities such as forestry and agriculture occur on a regional scale, while the remaining anthropogenic activities comprising mining, urban and or industrial land use, rural practises and salt water intrusion are localised.

7.2.1 Forestry

Forestry is the dominant land use in the study area (Figure 7-3) and accounts for an area of c.720 km². The area encompassed by forestry in the eight quaternary catchments in the study area is shown below in Figure 7-4 and presented in Table 7-3.

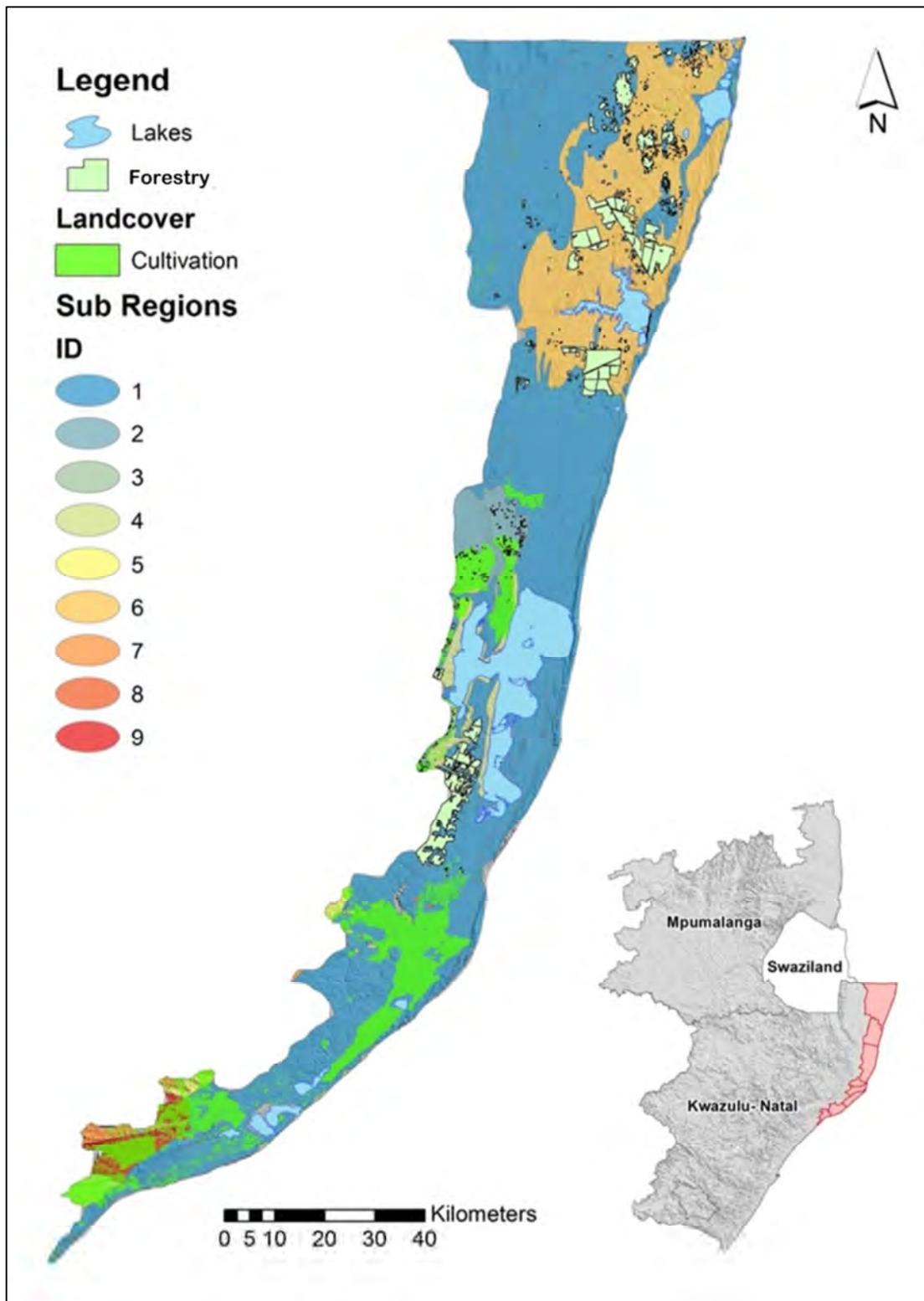


Figure 7-4: Distribution of Forestry across the Nine Laterally Delineated Hydrostratigraphic Units

Table 7-3: Area under Forestation per Quaternary Catchment, (WRC, 2005).

Quaternary Catchment	W12F	W12J	W13B	W23C	W23D	W32B	W32H	W70A
Catchment Area (km ²)	399.0	485.0	222.0	313.0	248.0	935.0	1,276.0	2,589.0
Forestation Area (km ²)	38.4	134.4	37.1	134.6	45.8	26.8	143.5	158.5

Afforestation has a significant influence on the water balance of an area as it consumes water via interception and evapotranspiration (ET) and induces stream flow reduction. Evapotranspiration is defined as the total evaporative losses from forests which include transpiration from dry canopies as well as evaporation from wet canopies and the soil surface. Stream flow reduction refers to the decline in the water balance of a catchment which is attributed to the consumption of water by forest stands, (Tewari, 2003). The anthropogenic impacts of forestry are discussed below using case studies. Photographs of forestry in the study area are presented in Figure 7-5.



Figure 7-5: Plantations in Northeastern KwaZulu-Natal, (modified after Karumbidza, 2006).

The Eastern and Western shores of Lake St. Lucia (W32H catchment, Figure 7-3) are covered by extensive commercial forests of *Pinus Elliottii* (Pine) and *Eucalyptus grandis* (Eucalyptus), (Kelbe and Germishuyse, 2010). Investigations undertaken by Rawlins and

Kelbe (1991) revealed that in comparison to the surrounding natural vegetation, Pine plantations at the Eastern Shores State Forest transpired water at a rate of 1.2 mm day^{-1} faster than that of the surrounding grasslands. Also, groundwater table recession rates under the Pine plantations were at 2.6 mm day^{-1} in comparison to the groundwater table recession rate of 1.7 mm day^{-1} under grasslands. The difference in transpiration rates denoted that the plantations lose water at a rate of 1.9 mm day^{-1} faster than that of the grasslands, (Rawlins and Kelbe, 1991). In addition, the Pine and Eucalyptus plantations have negatively impacted groundwater discharge to the local drainage system as seepage rates into the False Bay, southern lakes and estuary sections were reduced by $>5,000 \text{ m}^3/\text{d}$, (Kelbe and Germishuise, 2010).

The investigation undertaken by Brites and Vermeulen (2013) at the Nyalazi Plantation (comprising indigenous vegetation, Eucalyptus and Pine plantations) situated on the Western Shores of Lake St. Lucia confirmed that areas underlain by mature Pine plantations were characterised by a depressed groundwater table of c.5.82 mbgl. In comparison, the groundwater table in areas adjacent to mature Pine plantations which were vegetated by shrubs and natural grass was at c.1.08 mbgl. Furthermore, the Eucalyptus plantations of varying maturity had a profound impact on the receding groundwater table which declined between 10 m to 16 m over a period of 13 years whereas the groundwater table in the area overlain by indigenous trees, declined between 4.5 m to 7.3 m over the same period. This illustrates the high consumptive use associated with Eucalyptus plantations in comparison to indigenous vegetation.

Along the eastern shorelines of Lake St. Lucia, several groundwater dependant wetlands existing within the pine plantations were gradually destroyed by the receding groundwater table which was a function of the extensive plantations. These commercial plantations were removed between 2003 and 2005. Subsequently, the groundwater table rebounded resulting in remnant tree stubs being inundated by half a meter of water in re-emerging wetlands as displayed in Figure 7-6, (Kelbe and Germishuise, 2010).

Similarly, groundwater was recognised as an integral component of Lake St. Lucia which therefore prompted the development of a management strategy to increase groundwater flux into the Eastern Shores of Lake St. Lucia. The success of the management strategy was assessed by Vaeret *et al.*, (2009) who used a numerical groundwater model.

Based on the findings of the model, it appeared that the replacement of extensive Pine plantations with grassland in conjunction with a strict burning regime had increased groundwater seepage to Lake St. Lucia. The simulated model indicated that a significant rise in the groundwater table was observed when Pine plantations were replaced with grassland and there was an increase in precipitation, (Vaeret *et al.*, 2009).

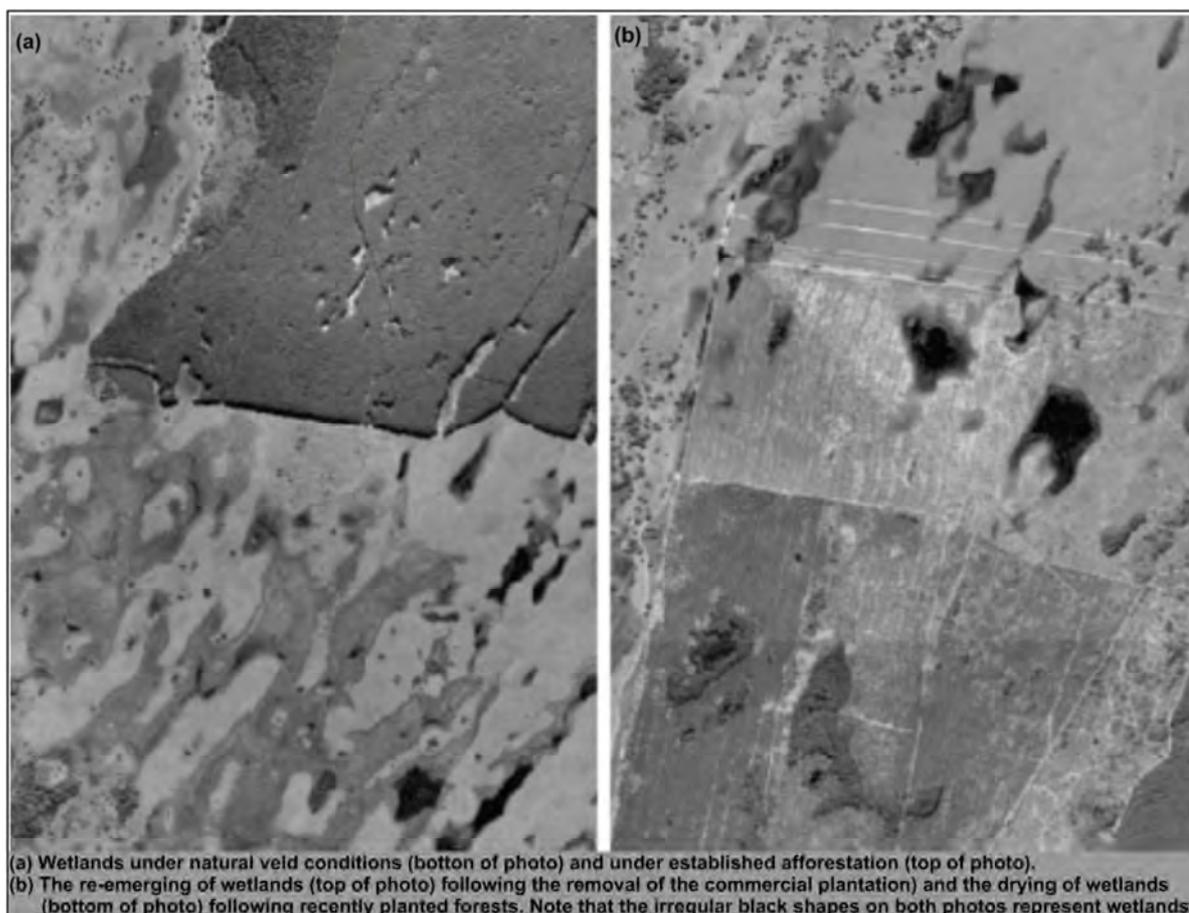


Figure 7-6: Impact of Forestry on Wetlands, (modified after, Kelbe and Germishuys, 2010).

7.2.2 Agriculture

Population growth, increased standards of living and associated demand for food production are key factors that are responsible for the expansion and intensification of agricultural production, (BGS, 2009). Agricultural activities which may cause groundwater pollution are summarised below, (Usher *et al.*, 2004):

- Application of inorganic fertilisers, pesticides and herbicides.
- Application of sewage sludge as a soil amendment.
- Disposal of waste water from abattoirs.
- Irrigation with waste water.
- Storage and inappropriate disposal of animal waste from dairies, feedlots and piggeries which is likely to give rise to pathogenic bacteria, viruses and parasites. Biological pollution may possibly cause diseases such as typhoid fever, polio, cholera and hepatitis.
- Accidental spillage of agrichemicals.

Irrigation ensures that fallow land is productive, allows for crop intensity on cultivated land and prolongs the growing season, (BGS, 2009) while the tillage of land changes the

infiltration and runoff characteristics of the landscape and directly impacts on recharge to surface water and groundwater bodies, (Winter *et al.*, 1998).

In many irrigated areas, approximately 75% to 85% of the irrigated water is cumulatively lost via evapotranspiration and retention in the crops. The remainder of water infiltrates through the soil and recharges groundwater or it returns to local surface water bodies via a drainage system. Large irrigation systems are typical of areas that receive low precipitation therefore the quantity of irrigation water that recharges groundwater often exceeds the volume of recharge from precipitation. The anthropogenic impact associated with irrigation is that poorly drained soils characterised by a shallow groundwater table become waterlogged, while loose soils are eroded and transported via surface runoff and eventually reach surface water bodies where excessive sedimentation occurs, (Winter *et al.*, 1998). Furthermore, capillary action allows the groundwater to advance to the surface where evaporation occurs resulting in the salinization of soils and water, (BGS, 2009).

Groundwater abstraction for irrigation represents the principal use of groundwater globally (BGS, 2009) and in South Africa, the agricultural sector utilises the highest volume of groundwater in all arenas of the agricultural sector (irrigation and stock watering purposes), (Parsons, 2004).

Often, aquifers are excessively exploited to meet irrigation demands causing adverse impacts which develop simultaneously with abstraction, are rarely observed immediately and are often very challenging to reverse, if possible. Foster *et al.*, (2000) identified several anthropogenic impacts of excessive groundwater abstraction which is summarised below:

- Borehole yield, spring flow and river base flow reduction which is attributed to the aquifer's hydrogeological properties.
- Phreatophytic vegetation stress on account of the receding groundwater table.
- Ingress of contaminated water from the adjacent perched aquifer or river which is a function of the operational boreholes cone of depression generated through abstraction.
- Saline water intrusion which is a function of distance to the ocean and is an irreversible impact. Coastal aquifers are regarded most susceptible to saline intrusion.
- Aquifer compaction which translates to reduced transmissivities in the aquifer which is also considered irreversible.
- Land subsidence and associated impacts which is caused by the vertical compressibility of the overlying or interbedded aquitard. Alluvial deposits are highly susceptible to subsidence whereas consolidated formations are unlikely to be affected by subsidence.

- Socio-economic impacts as shallow domestic water supply wells utilised by rural households, often dry up on account of the receding groundwater table which is attributed to excessive abstraction by deep water supply boreholes.

BGS (2009) also highlighted agrochemical use as a major anthropogenic impact. The demand for crop production is met via the application of fertilisers and a wide spectrum of pesticides which have unique chemical properties and toxicities as some pesticides are soluble in water while others tend to sorb to the soil, (BGS, 2009). Pesticides may have a significant impact on the groundwater resource of an area if the aquifer is capped by permeable soils, shallow groundwater tables, has low porosity (dilution is minimal) and the pesticide is stable and mobile, (Sililo *et al.*, 2001).

Fertilisers are enriched in inorganic compounds and nitrate. Nitrate is highly soluble, mobile and resistant to degradation under aerobic conditions. It is also the main nutrient leached into groundwater in comparison to phosphate which is retained in the clay layers via adsorption. Nitrogen loading is accelerated by intensive farming and can also occur where irrigation is excessive and not carefully controlled, (BGS, 2009).

High concentrations of nitrate in groundwater results in eutrophication of surface water bodies causing widespread algal blooms and macrophyte growth. The accumulation of nutrient compounds in excess of the ecosystems' requirements may impact on the biodiversity and functioning of aquatic biota, (DWAF, 2002).

A case study highlighting the anthropogenic impacts of sugar cane farming, derived from Case Study 3 - Kelbe and Germishuise (2010), is presented below:

The Siyaya Estuary which is situated near the town of Mtunzini (southernmost point for the study area) displays anthropogenic impacts attributed to the historical practise of sugar cane farming. The study revealed that pre-1990, the land use in the Siyaya catchment was almost entirely encompassed by intensive sugar cane farming which caused extreme sedimentation that hindered flow into the Siyaya Estuary. The sugar cane plantation marred the landscape and degradation was particularly evident along the riverine section where nearly all streambeds were incorporated into the plantation and indigenous riverine vegetation was almost absent.

Post-1990, commercial sugar cane farming in the catchment ceased and was replaced with forest plantations. Following the land use transformation, a marked improvement in the hydrological flow and reduction in sediments has been observed in the estuary. However, the anthropogenic impact of the historical sugar cane plantations is still far reaching with residual sediment in the estuary supporting the growth of reeds. Most importantly, baseflow contribution to the Siyaya River and Estuary was drastically reduced and requires intervention by the Catchment Management Agency. The status of Siyaya Lagoon is shown

in Figure 7-7. The reader is also referred to Section 7-2.4 where a case study of the anthropogenic impacts of industry and agriculture on the Umhlathuze River is discussed.

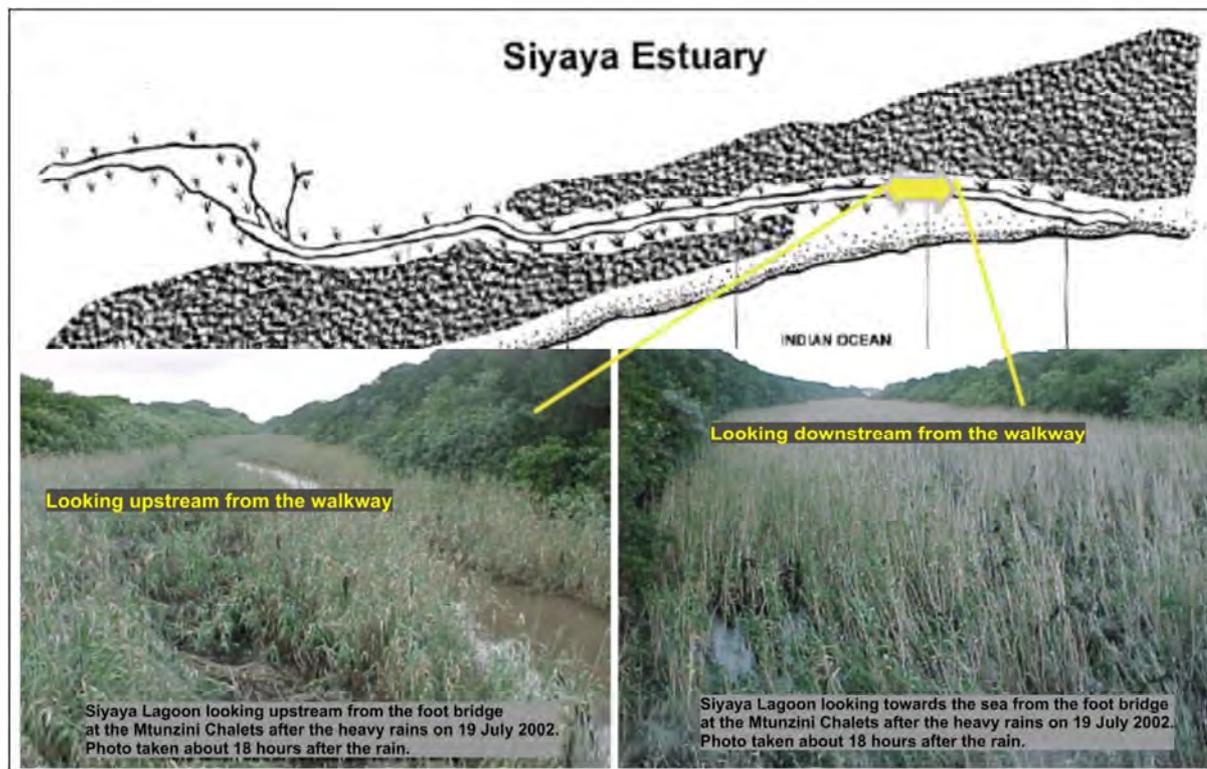


Figure 7-7: Photographs of the Siyaya Lagoon, (modified after, Kelbe and Germishuyse, 2010).

7.2.3 Mining

“The magnitude of the threat from mining activities is dependent on whether precautionary measures are taken to prevent pollution, but in many cases, the scale of mining operations is such that groundwater pollution cannot be completely avoided”, (Usher *et al.*, 2004).

Mining of heavy mineral deposits concentrated in the sand dunes of the ZCP occurs in the W12F and W12J catchments which are situated relatively north-south along the coast of Richards Bay (Figure 7-3).

The process of mining and its associated environmental impacts is regarded as highly confidential hence literature on the aforementioned is extremely limited. Therefore, the processes involved in the mining of heavy mineral deposits and its associated anthropogenic impacts are derived from Golder (2013), unless otherwise stated.

Richards Bay Minerals (RBM) has mining rights to three mineral lease areas comprising Tisand, Zulti North and Zulti South. The length of the mineral lease area is c.37 km. Heavy minerals comprising ilmenite, zircon and rutile are extracted from the ore body via two mining methods which are summarised below and photographs of the mining processes are shown in Figure 7-8.

Dredge mining is the dominant mining method utilised and requires the vegetation and topsoil to be removed thereby allowing for the establishment of a freshwater pond in the dunes upon which a dredger and concentrator plant floats on. The dredger which advances at a rate of 2 to 3 m/d, unearths the mining face with a rotating bucket, cutter or high-pressure water jet causing the sand to collapse into the pond thereby creating a slurry of sand, water and heavy minerals in the pond below. The slurry is pumped into the floating wet concentrator plant where gravitational processes are used to separate the heavy minerals from the sand which are subsequently stockpiled alongside the artificial temporary dam as a heavy mineral concentrate. The concentrate is dewatered and transported for processing to the Final Product Site following which excess water is returned to the pond. The tailings are stacked behind the southern sections of the pond where the dunes are re-shaped by tail stackers to reflect the landscape of pre-mining conditions.

Dry mining operations are utilised in areas that are inaccessible or inappropriate for dredge mining methods on account of shallow deposits, hard bands of rock or a series of disconnected ore bodies. Dry mining involves the mechanical mining of sand by front end loaders. Sand is then deposited into hoppers with screening abilities and subsequently deposited into a mobile unit which creates a slurry. The slurry is pumped to the concentrator plants in the relevant mining ponds for further processing as described above. Dry mining enables RBM to recover additional ore thereby extending the life of the mine.

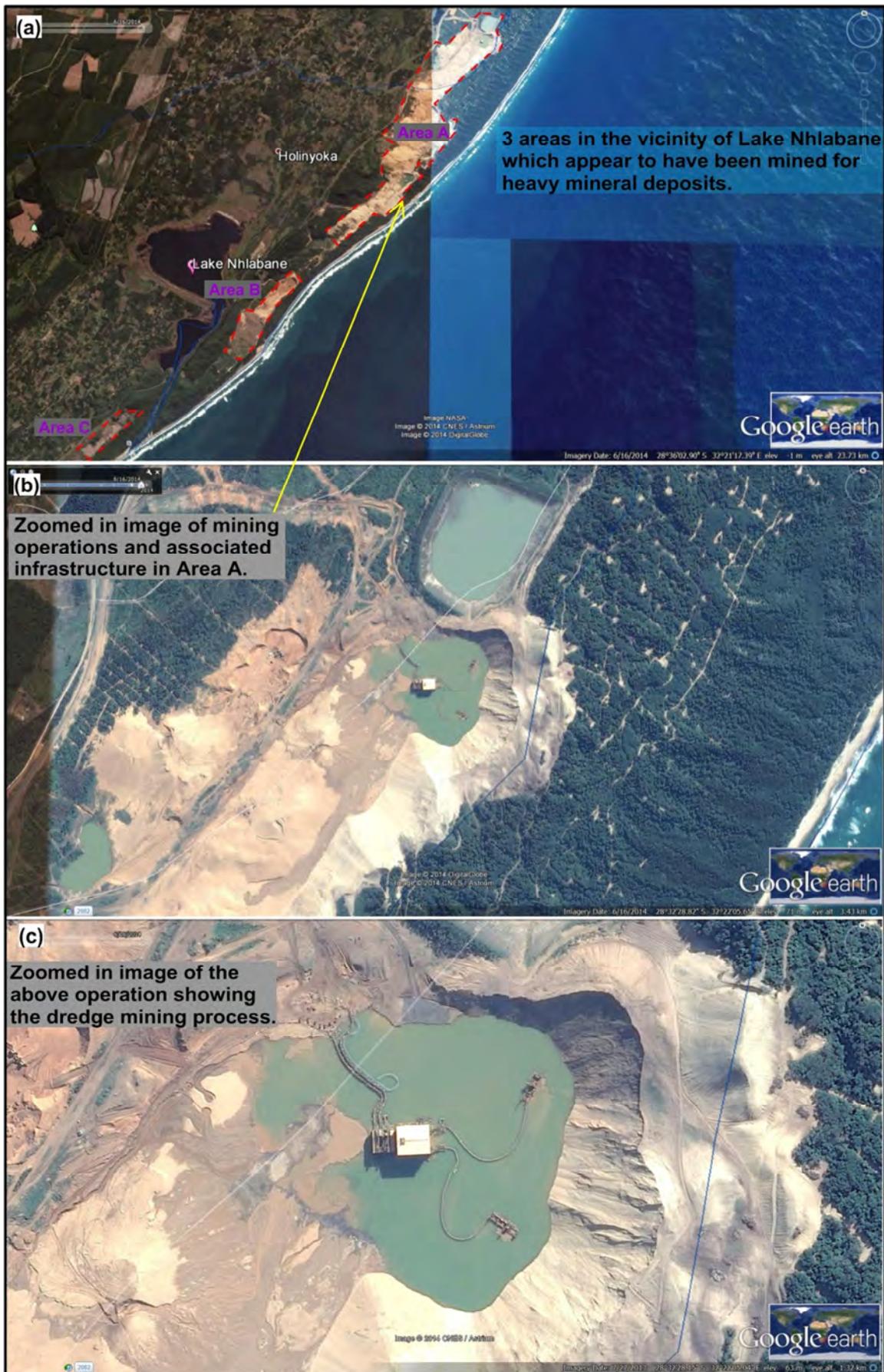


Figure 7-8: Mining in the Vicinity of Lake Nhlabane, (Google Earth, 2014 (image (a) and (b)) and 2013 (image (c))).

Anthropogenic impacts of mining on the aquifer, geology and surface water bodies are derived from Golder (2013) (unless otherwise stated) and are listed below:

- Destruction of the natural landscape, flora and fauna through the mining process.
- The development of erosion scars that have formed by the egress of water flow between the clay and underlying strata is likely to be exasperated by mining due to the elevation of the perched aquifer.
- Erosion scars reduce dune stability and can prompt slumping onto the beach as slump occurrence was found to be accelerated by groundwater fluctuations associated with pond water and tailing stacks.
- Slope instability induced by dredge mining can result in the failure or subsidence of dunes and adjacent stacking locations.
- Potential pollution of surface and groundwater and subsequent impact on groundwater quality via seepage from the mining ponds, concentrate stockpiles and associated sand tailings stackers.
- Gradual increase in sulphate and calcium levels of the surrounding surface water bodies which corresponds with an increase in TDS concentrations in the surrounding streams.
- Following the completion of the dredge mining process, the sand is randomly redistributed and therefore the cover sands lose their bedding in the process of dredging and also loose c.5% of their mass due to the extraction of heavy minerals.
- The process of removing and redistributing the topsoil severely disturbs the soils structure as well as its mineralisation and chemical exchange processes within it. In addition, the soils are characterised by low water retention capacity which translates to rapid drainage and therefore vegetation is likely to dehydrate in hot weather conditions.
- Mining causes a reduction in fresh organic matter, litter and nutrient concentrations in soils over a prolonged period. Therefore, the soils are characterised by a major depletion in nitrogen, fixed carbon and phosphorous and are unlikely to support the growth of coastal dune forests.
- Mining also reduces the silt and clay fraction in the tailings which equates to reduced soil fertility, (Golder, 2013).
- Naturally occurring radionuclides (uranium, thorium and radium) typically associated with heavy mineral deposits are exposed through mining processes, (Golder, 2012).

7.2.4 Urban and Industrial Land Use

Urban and industrial land use cumulatively occurs in the W12F and W12J quaternary catchments (Figure 7-3). According to Usher *et al.*, (2004), groundwater pollution in urban areas may arise from the following activities:

- Sanitation infrastructure and the presence of underground sewage infrastructure, waste water treatment works and maturation ponds which have the potential to pollute if they are poorly managed, not properly lined and rupture.
- Storm water collection and grey water disposal infrastructure.
- Irrigation and agrochemical application to sports fields and golf courses.
- Cemeteries.
- Underground storage of petroleum products which have the potential to leak.
- Disturbance or damage to aquifers during construction.
- Activities which alter recharge (hardening of surfaces by construction).
- Excessive or uncontrolled groundwater abstraction.

To accommodate the increase in urban growth, the development of residential areas often requires deforestation and the removal of wetlands and riparian vegetation. The anthropogenic impact associated with deforestation is a decrease in evapotranspiration, groundwater infiltration and baseflow contribution. On the contrary, there is an increase in surface runoff and soil erosion. However, the impact of the removal of riparian vegetation and wetlands is far more profound. Not only does the benefit of flood mitigation and erosion control disappear but also the ecosystems and natural processes that maintain water quality are destroyed, (Winter *et al.*, 1998).

Storm water runoff may contain pathogenic bacteria which has the potential to impact groundwater users in the event of the contaminated runoff entering water supply sources. Groundwater pollution may arise from discharge into a surface water body via leakage from a pipeline, discharge to an artificial recharge basin etc., (Sililo *et al.*, 2001).

Urban and industrial activities generate vast quantities of wastewater or effluent which are discharged in the following ways, (BGS, 2008):

- Raw or untreated effluent directly into the subsurface or via streams, rivers and canals to the aquifer.
- Disposal to municipal sewer systems which may have sewage treatment plants.
- Treatment of effluent on-site before disposal by the methods stated above.

In their numerical model, Kelbe and Germishuysen (2001) also discussed the influence of land use on the water balance of Lake Mzingazi. According to their findings, impermeable

road surfaces were associated with reduced recharge while deep rooting trees would decrease discharge and cumulatively have a significant impact on the water balance of the shallow unconfined aquifer.

Cemeteries pose a threat to groundwater resources as decomposing bodies significantly increase microbiological activity in the subsurface. Profound impacts of pollution arising from cemeteries are likely to be observed in areas characterised by high MAP and a shallow groundwater table. However, the aforementioned may be exasperated by an increased rate and density of burials, (Sililo *et al.*, 2001).

Analyses of a water sample collected from Lake Sibaya at Banda-Banda (Table 7-4), indicated that the elevated EC concentration exceeded the South African Water Quality Guideline (1996). The major cations and anions which were significantly elevated also exceeded the South African Water Quality Guideline (1996) and represented the highest concentrations reported for the catchment at the time of sampling. The observed water quality was attributed to the presence of numerous accommodation venues which were equipped with septic tank systems. In addition, the hyper saline conditions were responsible for a large number of fish deaths, (DWAF, 2002).

Table 7-4: Water Quality Data from Lake Sibaya at Banda-Banda, (DWAF, 2002).

Name	Na-Diss-Water (mg/L)	Mg-Diss-Water (mg/L)	SO ₄ -Diss-Water (mg/L)	Cl-Diss-Water (mg/L)	K-Diss-Water (mg/L)	Ca-Diss-Water (mg/L)	EC-Phys-Water (mg/L)
Lake Sibaya at Banda-Banda	9,379.25	1,139.92	2,469.86	17,041.85	354.78	399.68	4,297.95

Industrial activity utilises water in a variety of ways ranging from heating and cooling to the transport of dissolved substances and being a component of the industrial product itself. The volume of groundwater abstracted for industrial use has not been quantified however; a greater concern is the impact on the water quality of the aquifer, (BGS, 2008).

According to Morris *et al.*, (2003), the impact of an industry on the surrounding environment is determined by the manner in which waste is disposed of, waste storage methods, the level of pollution control procedures and the vulnerability of the aquifer. However, the discharge of industrial effluent is known to cause deterioration in water quality with acidification, salinization, increase in TDS and heavy metal concentrations regarded as the anthropogenic impacts, (DWAF, 2002).

Specific to the study area, the concentration of industries in the Richards Bay area is likely to have contaminated the aquifer as effluent discharge and leakage of waste products is a

major concern. Despite the localised occurrence of pollution, it is believed that future groundwater abstraction will propagate the pollution plume, (DWAF, 2002). The common sources of industrial groundwater pollution are shown in Table 7-5.

Table 7-5: Common Source of Groundwater Pollution from Industry, BGS (2008) and modified after Morris *et al.*, (2003).

Source	Mechanism or Main Contributing Factor
Underground and surface storage tanks, processes and effluent pipework or other transfer system.	Undetected leakage or inadequate bunding to retain major failures.
Industrial sewers or collectors.	Leakage because of poor maintenance.
Soak-pits and waste injection wells.	Pollution because of inappropriate disposal practise.
Bulk chemical storage areas.	Poor handling and storage procedures. Leaks.
Liquid effluent and process lagoons.	Leakage because of poor construction or maintenance.
Waste disposal sites.	Leakage of leachate through poor construction or failure of design.
Accidental or catastrophic discharge.	Plant fire, explosion, impact and loss of material to ground.

A case study of the anthropogenic impacts of industrial and agricultural activity on the Umhlathuze River, derived from Mthembu *et al.*, (2012), is summarised below:

The Umhlathuze River is situated next to Richards Bay where the surrounding area is predominantly encompassed by sugar cane farms and a multitude of industries. Approximately 63% of the rural communities situated adjacent to the Umhlathuze River utilise water from it for potable purposes (without prior treatment). Therefore, they are likely to be exposed to water-borne illnesses and are at risk of ingesting carcinogenic substances. Major concerns around the industrial and agricultural practises along the Umhlathuze River are listed below:

- Deposits along the banks of the Umhlathuze River are mined by several companies and effluent generated during the mining process is discharged directly into the river causing microbial and chemical pollution.
- Commercial sugar cane farms utilise a substantial volume of fertilisers and during periods of heavy rainfall, the fertiliser is eroded and incorporated into the surface runoff which discharges into the Umhlathuze River and subsequently causes eutrophication.
- Certain industrial companies situated along the Umhlathuze River are not equipped with effluent treatment or disposal systems. Therefore, industrial effluent drained or washed through the respective companies' stormwater drainage system is subsequently discharged into the Umhlathuze River.

Water samples collected from four sites comprising Kwa-Dlangezwa (agricultural area), Felixton Bridge and Mzingazi (agricultural and industrial areas) and the Umhlathuze Station (industrial area) along the Umhlathuze River were analysed to assess the degree of pollution associated with these two main land uses.

The analyses indicated that samples collected from areas affected by industrial activities were characterised by an acidic pH in comparison to the high pH recorded in areas affected by agricultural activities. Faecal coliforms were detected at elevated concentrations in the Felixton and Kwa-Dlangezwa samples and were attributed to agricultural practises. Compounds such as nitrate, phosphate and ammonia were detected at high concentrations in agriculturally affected areas while heavy metals were detected at elevated concentrations in samples collected from the Umhlathuze Station and Mzingazi. However, dilution of the respective pollutants of concern was recorded upon entering the river. The study concluded that samples collected of the industrial effluent and agricultural waste at its discharge points along the Umhlathuze River exceeded the allowable limit stipulated in Department of Water Affairs Domestic Water Use Guideline (1996).

7.2.5 Rural practises

The study area is characterised by largely sparsely populated rural dwellings which are remotely located (Figure 7-3 and 7-9). These rural households are often characterised by high levels of poverty and inadequate sanitation. Therefore, their livelihoods are maintained by the practise of subsistence agricultural and livestock farming of which they are oblivious of the repercussions associated with such practises. Water quality issues (both surface water and groundwater) coupled with over grazing of livestock and poor land management practises causes erosion and sedimentation of nearby surface water bodies. Furthermore, increased livestock concentrations in densely populated rural areas are responsible for elevated *E. Coli* concentrations, (DWAF, 2002).

A case study of anthropogenic impacts of pit latrines in rural communities which is derived from Still and Nash (2002) is presented below:

According to Still and Nash (2002), rural communities in the study area commonly use shallow unprotected wells that are burrowed in or near river beds and pans. Groundwater abstracted from these resources is consumed without treatment. As these communities lack basic waterborne sanitation, the utilisation of pit latrines is common. Faecal waste is characterised by various pathogens which exhibit varying degrees of mobility. Viruses and bacteria are filtered through the soil in comparison to protozoa and parasitic worms which can migrate with the seepage.

Mobility of pathogens is a function of the type of seepage flow, size of the soil particles, soil pH and temperature and under the right conditions, pathogens can still be present >30 m

away from the source. The life span of pathogens in soil can range from 10 to 100 days. In addition, faecal waste elevates the nitrate concentration in the soil.

Analyses of groundwater samples collected from protected public and private tube wells, rings wells and unprotected public ring wells situated between 1 m to 90 m of pit latrines and in the direction of groundwater flow indicated the following:

- Elevated nitrate concentrations were detected in groundwater samples closest to pit latrines.
- Nitrate concentrations were higher in wells utilised by a large number of people in comparison to private wells. This trend was attributed to the wastage of water by more people and therefore via the percolation of waste water, the nitrates contained in the soil around the well were leached.
- In comparison to private wells, public protected wells had a high concentration of *E. Coli* while unprotected wells displayed the highest *E. Coli* concentration.
- Overall, the best water quality was detected in private wells while unprotected wells had deteriorated water quality and as they were impacted by several pollution sources.

Worthington (1978) examined bacterial pollution sources and indicated that the unsaturated vadose zone is most susceptible to pollution. However, bacterial pollution (as described in the vicinity of Lake Mzingazi) is localised and bacteria is removed during percolation into the subsurface environment. This is particularly evident as the case study above indicated that porous sands were effective in filtrating bacteria and that pit latrines and public water points affect the groundwater nitrate concentrations on a local scale, (Still and Nash, 2002).

It is important to note that water contaminated by faecal matter is the medium for the spread of diseases such as dysentery, cholera and typhoid, (DWAF, 2002).

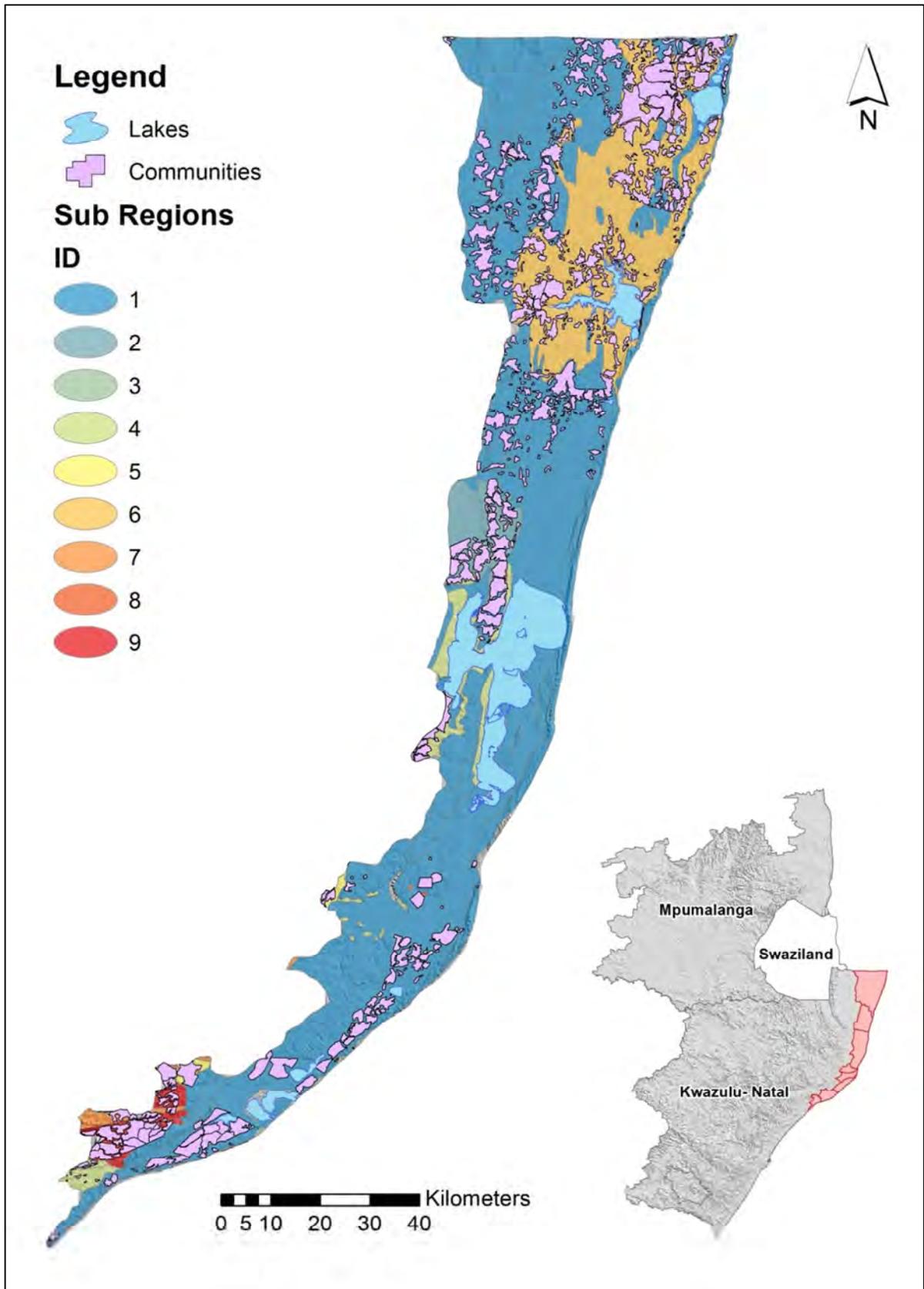


Figure 7-9: Distribution of Informal Settlements across the Nine Laterally Delineated Hydrostratigraphic Units.

7.2.6 Salt water intrusion

The impact of salt water or saline intrusion is applicable to boreholes situated along or in close proximity to the eastern peripheral study boundary which is represented by the Indian Ocean (Figure 7-3). The most apparent source of pollution is the ocean. As sea water is denser than groundwater, saline water is expected to occur below groundwater. A salt wedge which is present along the coastline and estuaries prevents the downward mixing of low salinity water and enables fresh groundwater to discharge closer to the shore. Due to the presence of the salt wedge, deepening of boreholes for increased groundwater abstraction increases the potential for sea water intrusion, (Campbell *et al.*, 1992).

According to Barlow (2003), salt water intrusion is caused by a disturbance in the natural balance between fresh water and sea water. This disruption is predominantly induced by excessive groundwater abstraction while other factors such human activities that lower groundwater levels, reduced groundwater flux to coastal waters and reduced groundwater recharge attributed to urbanisation are considered to have little influence. The mechanism for salt water intrusion is a function of the hydrogeological environment and is listed below, (Barlow, 2003):

- Lateral intrusion directly from the ocean.
- By upward intrusion from deeper saline zones of a groundwater system.
- Downward intrusion from coastal waters.

A case study of salt water intrusion into the Mzingazi River, which is derived from Cyrus *et al.*, (1997), is presented below:

Lake Mzingazi is situated north of Richards Bay. Drought conditions and excessive abstraction of water from Lake Mzingazi for domestic and industrial use caused the freshwater flux from the lake to cease in February 1992. Consequently, the flux to the Mzingazi River ceased as well. This led to the intrusion of salt water from the Richard's Bay and the associated impacts are summarised below:

- The salinity of Mzingazi River was almost similar to that of sea water on account of very weak dilution caused by fresh water seepage from Lake Mzingazi which itself had stopped three months prior to the investigation (this particular case study).
- Death of several swamp forest trees and plants in herbaceous swamp areas including defoliation of other trees.
- In some places, saline water had intruded into the groundwater of the swamp forests and herbaceous swamps for >20 m from the river bank.
- Intrusion of saline water extended for >10 m away from the Mzingazi River bank.
- Generally, the pH in the groundwater was very acidic (pH of <4).

- A hydrogen sulphide odour occurred in areas recording acidic pH and was assumed to be associated with anaerobic activity which was inapt for plant root growth.
- There was regular but less extensive flooding of the already impacted area by saline water on every spring tide.

8 Conclusions and Recommendations

The Zululand Coastal Aquifer is the largest primary porosity aquifer in South Africa, Meyer *et al.*, (2001). Due to the significant aerial extent of the aquifer and the occurrence of several distinct geological formations, the delineation of hydrostratigraphic units was mandatory to gauge the hydrogeological properties of the respective stratigraphic units.

Utilising Vegter's (2001) methodology, nine laterally delineated hydrostratigraphic units (Q and Qb; Qm; Qpd; Kz, Pv and Pvo; JI and Zn; Nhl, Nng and ZB; Tu and Ntu) were identified. However, insufficient data was a major shortcoming. In an attempt to gain further clarity, the hydrostratigraphic units were then delineated vertically using geological data derived from borehole logs. The vertical delineation produced four hydrostratigraphic units which were then chronologically aligned with the regional geology for the study area. These four hydrostratigraphic units are briefly summarised below:

- Hydrostratigraphic unit 1 encompasses the Sibayi Formation. Commonly referred to as the cover sands, the unconsolidated deposit is the most extensive hydrostratigraphic unit and is characterised by a shallow to unconfined groundwater table (<5 mbgl). Borehole yields were <0.4 L/s (GRIP data) and is widely exploited by rural communities across the ZCP. However, recent studies have reported that the cover sands are capable of producing yields of 10 to >25 L/s. Hydrogeological properties of the aquifer comprise high permeability (0.8 – 17 m/d) and porosity (23 – 38%). Transmissivity is high (c.7 - 140 m²/d) but variable across the study area. Hydrostratigraphic unit 1 has the highest horizontal (c.12 m/d) and vertical (c.0.5 m/d) hydraulic conductivity reported for the study area.
- Hydrostratigraphic unit 2 represents the sands of the Kwabonambi Formation. The influence of increased clay and silt fraction is illustrated by its reduced permeability, transmissivity, hydraulic conductivity and incessant vertical leakage. Hydrostratigraphic unit 2 represents the most prominent perched aquifer in the study area and is particularly evident in areas of elevated surface topography. Based on the above, hydrostratigraphic unit 2 is regarded as an aquitard.
- Hydrostratigraphic unit 3 comprises semi-consolidated sand intercalated with clay and lignite of the Kosi Bay and Port Dunford Formation. When exposed at the land surface, the clay enriched profile gives rise to a perched groundwater table which is illustrated by several expansive wetlands which occur in close proximity to Kosi Bay and Lake St. Lucia. Vertical leakage arising from the erratically distributed, low transmissivity deposits recharges the underlying geological formations. Therefore, hydrostratigraphic unit 3 is considered an aquitard that acts as a confining to semi-confining layer to the underlying strata.

- Hydrostratigraphic unit 4 consists of coquina and calcarenite of the Uloa Formation which are highly permeable and transmissive. Karst solution weathering further enhances porosity and is responsible for its irregular distribution across the ZCP. Boreholes intercepting the Uloa Formation have deep water levels and are frequently utilised for production purposes on account of their high yields (6.7 to 28 L/s). However, dry boreholes can be expected in areas where karst solution weathering is absent and the calcrete is strongly cemented. When present, hydrostratigraphic unit 4 is generally in contact with hydrostratigraphic unit 3 and is regarded as a leaky, semi confined to confined aquifer.
- The sporadically distributed siltstone and sandstone of the Zululand Group represents the hydrogeological basement for the ZCP. These low permeability deposits are characterised a deep groundwater table (21.3 to 42.6 mbgl) which is confined. The Zululand Group is renowned for its poor hydrogeological properties (reduced permeability and hydraulic conductivity) and yielding highly saline water. Therefore, it is frequently regarded as unsuitable for exploitation (borehole yields of <0.1 L/s) and subsequent potable use.
- It is important to note that with regards to the spatial distribution of the four hydrostratigraphic units, hydrostratigraphic unit 1 and 2 have extensive occurrence while the distribution of the remaining hydrostratigraphic units are limited and erratic across the Zululand Coastal Plain. Therefore, boreholes are unlikely to intercept all four hydrostratigraphic units including the hydrogeological basement in a vertically, sequential manner.

The discussions above advocate the presence of a dual aquifer system in the ZCP, comprising the shallow and deep aquifer. Despite local heterogeneities in the aquifer media, the hydrogeological properties discussed above suggest that hydrostratigraphic unit 1, 2 and 3 are representative of the shallow aquifer with the latter hydrostratigraphic units being associated with the deep aquifer. On account of compaction, vertical leakage in the respective shallow aquifers decreases with depth however, recharge to the underlying strata is continuous but at varying rates.

Quantification of the degree of surface water – groundwater interaction was undertaken using the Herold's Curve Fitting and the Saturated Volume Fluctuation (SVF) Methods. Using the naturalised flow data from WRC (2005), groundwater contribution to surface water bodies in the respective catchments ranged from an average of 2 Mm³/month (W32B catchment) to c.6.6 Mm³/month (W12J catchment). Using the SVF method, groundwater contribution to the lakes ranged from 0.1 Mm³/month (Lake Mgobozeleni) to c.60 Mm³/month (Lake St. Lucia). In addition, several case studies presented in this dissertation have highlighted that the majority of surface water bodies and associated

ecosystems exhibit a strong degree of groundwater dependency and constantly interact with the shallow aquifer.

The delineation of anthropogenic activities on the basis of land use have revealed that forestry and commercial sugar cane farming are the dominant anthropogenic activities in the study area and occur on a regional scale while mining, urban and or industrial land use, rural practises and salt water intrusion are localised. Forestry is renowned for causing stream flow reduction and the reduction in lake water levels.

Evaluation of several case studies for the respective anthropogenic activities have revealed that anthropogenic impacts vary in degree and spatial distribution and are principally governed by the geological and hydrogeological properties of the aquifer media including the type of pollutant discharged into the subsurface environment. The Zululand Coastal Aquifer is a highly transmissive deposit which has very little attenuating capacity and is characterised by shallow to unconfined groundwater levels therefore, the Zululand Coastal Aquifer is extremely vulnerable to pollution.

Recommendations

The installation of monitoring wells, borehole testing and water quality analyses were outside the proposed scope of work for this dissertation therefore, the GRIP and NGA database was extensively used. The GRIP and NGA data is irregularly distributed across the study area and data pertaining to some of the geological formations discussed in this dissertation was frequently absent or very limited. Based on the above, the author proposes that the following tasks be undertaken to augment the findings of this dissertation:

- Nested piezometers spatially represented of the ZCP should be installed to gauge the geological, hydrogeological and geochemical characteristics of the various stratigraphic units. The recommendations discussed above would assist in supplementing the aforementioned databases and creating robust datasets.
- Nested piezometers will also provide insight into the level of interaction between the various hydrostratigraphic units and surface water bodies. This level of detail has not been thoroughly investigated and warrants further research. Data derived from the aforementioned tasks will enhance the hydrogeological conceptual model for the ZCP.

Jeffares and Green (2012) reported that boreholes installed in the cover sands (hydrostratigraphic unit 1) generated yields ranging from 2.2 L/s to 20.0 L/s. Contrary to this, the GRIP database reported an average yield of <0.4 L/s. It is therefore recommended that additional investigations be undertaken to assess the groundwater resource potential of the cover sands, as it is laterally extensive. Understanding the hydrogeological properties of this aquifer will play a pivotal role in providing a sustainable domestic water supply to a multitude of rural communities situated across the Zululand Coastal Plain.

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<http://www.dwa.gov.za/hydrology>

<http://www.eea.europa.eu>

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Appendices

Appendix A: MAP Graphs for Several Quaternary Catchments in the ZCP

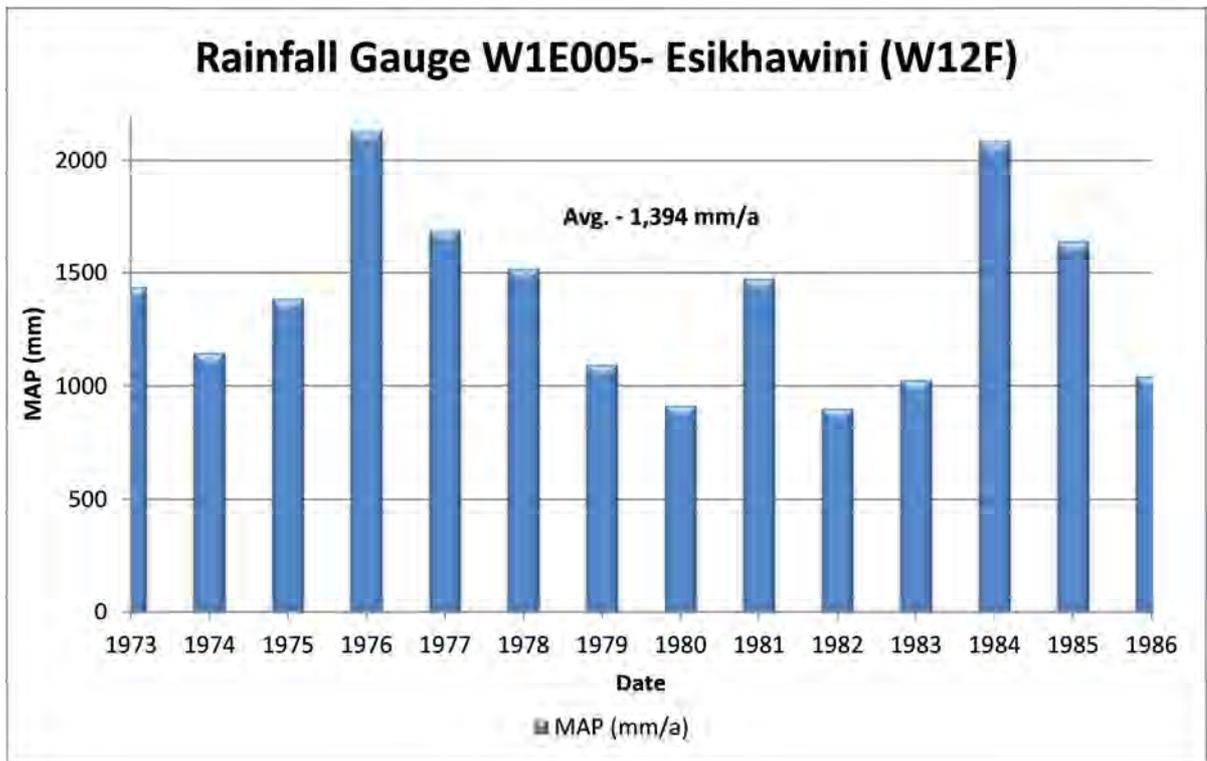


Figure A1-1: Mean Annual Precipitation Graph for the W12F Catchment.

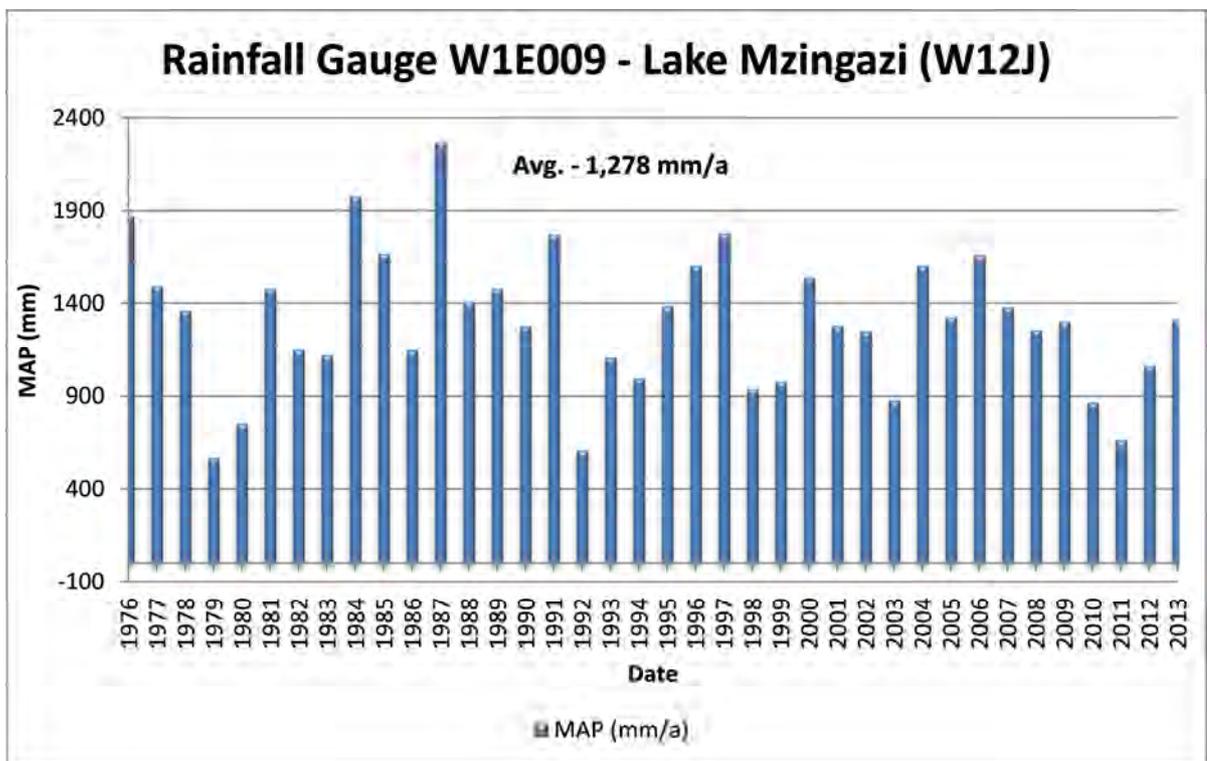


Figure A1-2: Mean Annual Precipitation Graph for the W12J Catchment.

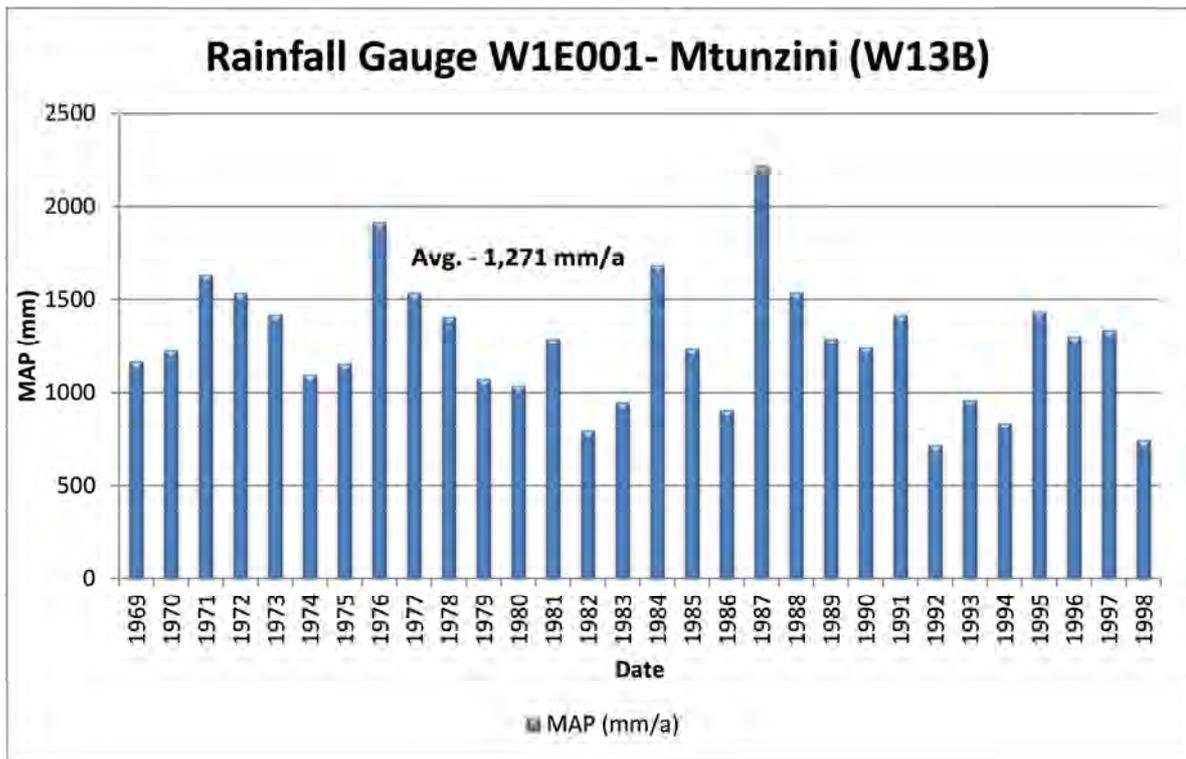


Figure A1-3: Mean Annual Precipitation Graph for the W13B Catchment.

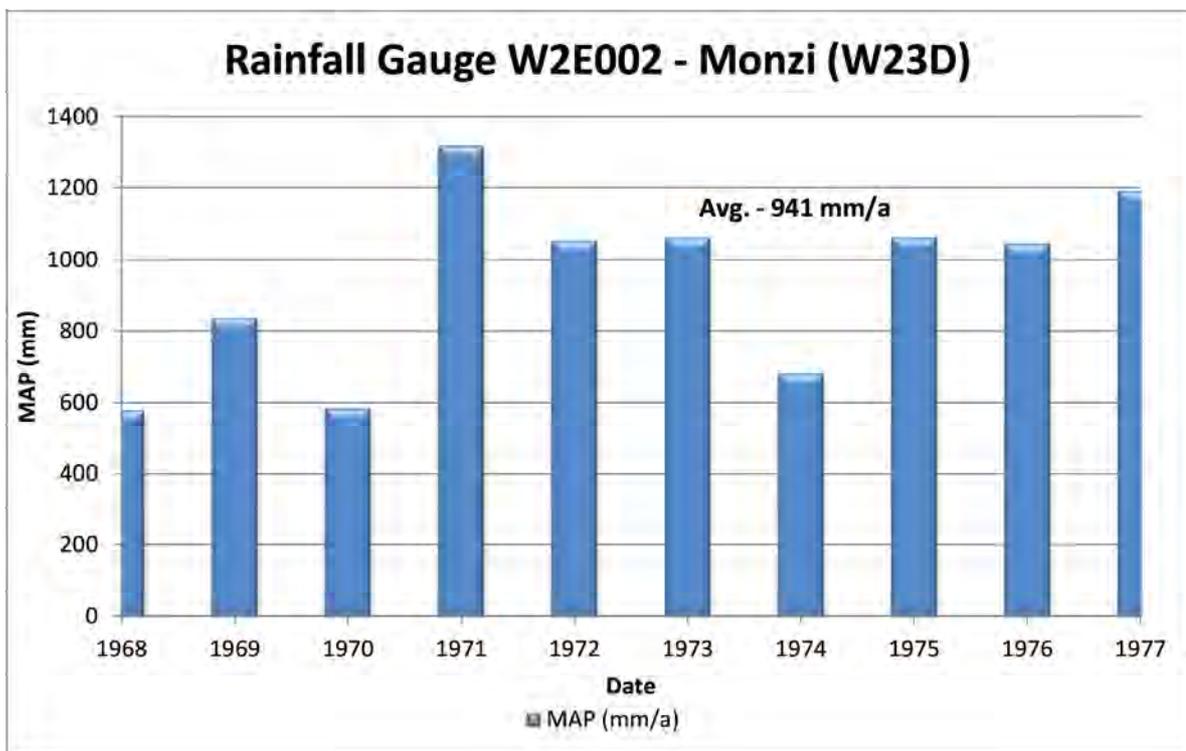


Figure A1-4: Mean Annual Precipitation Graph for the W23D Catchment.

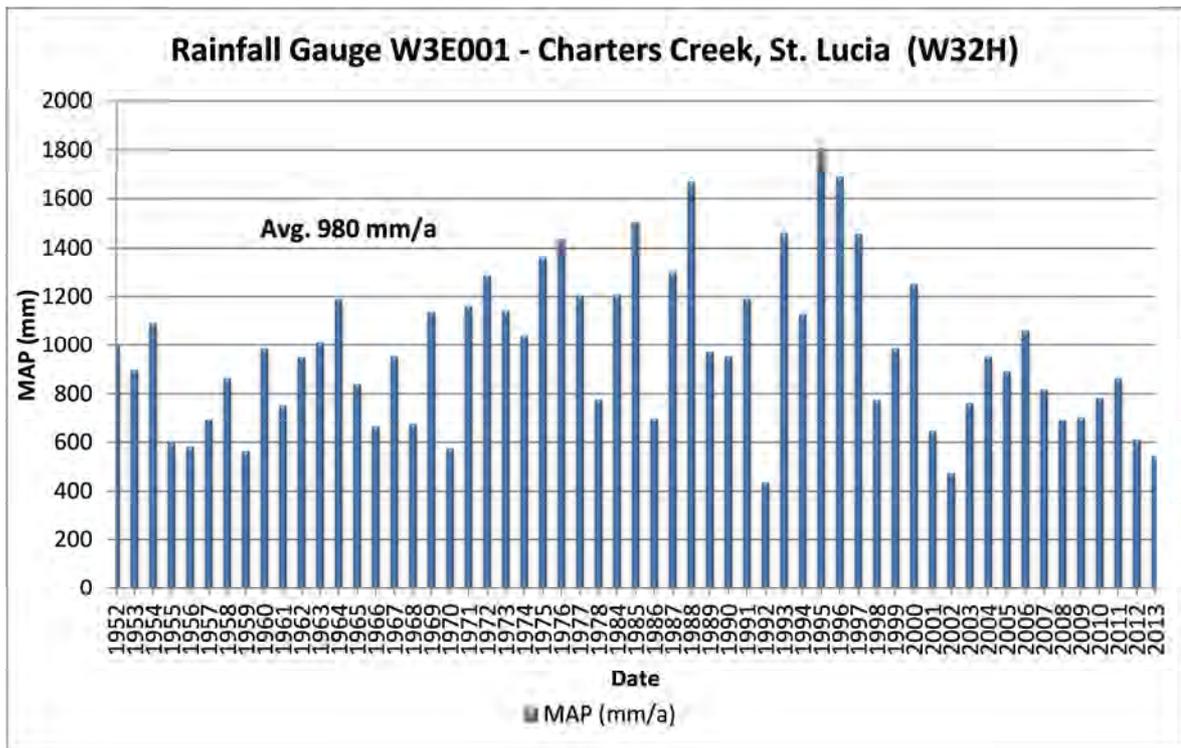


Figure A1-5: Mean Annual Precipitation Graph for the W32H Catchment.

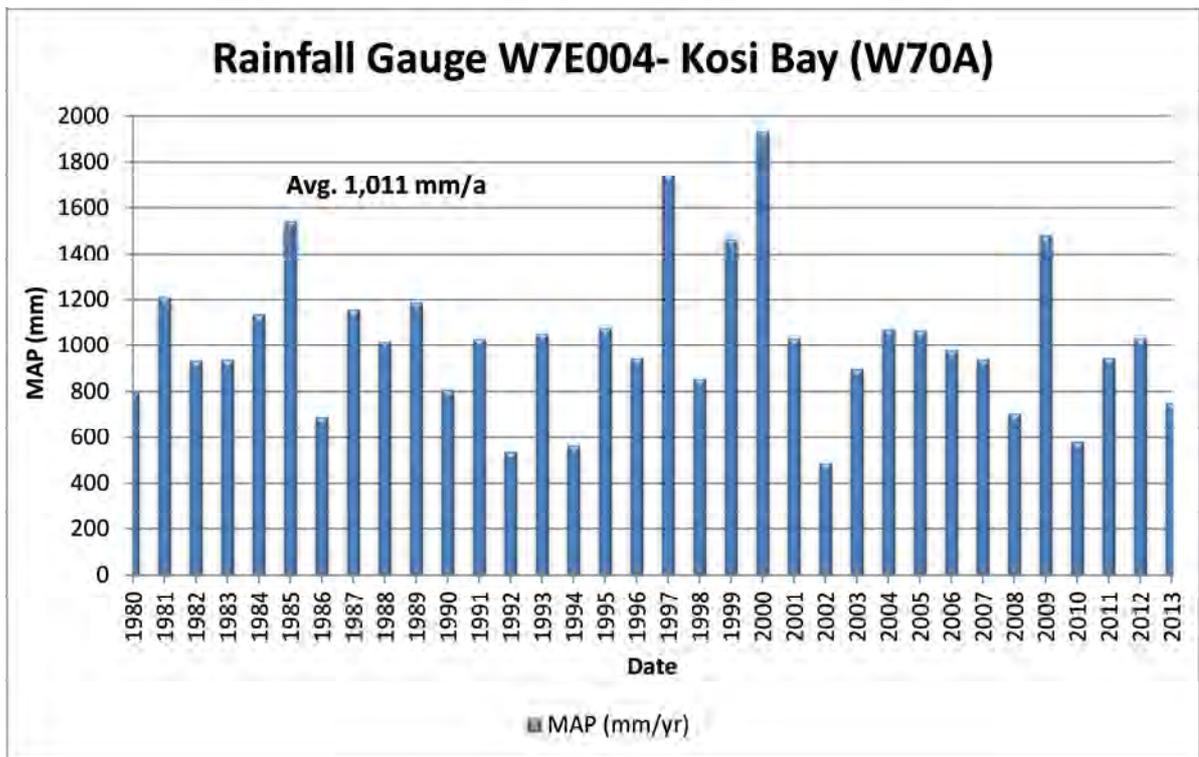


Figure A1-6: Mean Annual Precipitation Graph for the W70A Catchment.

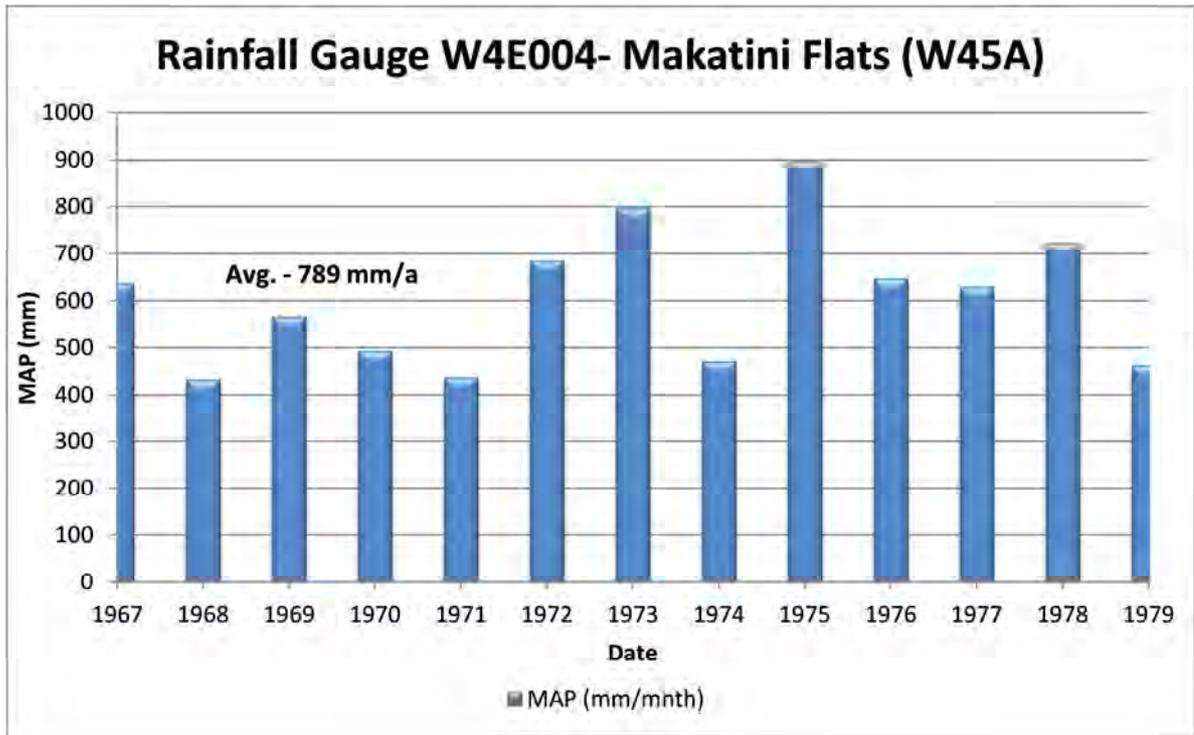
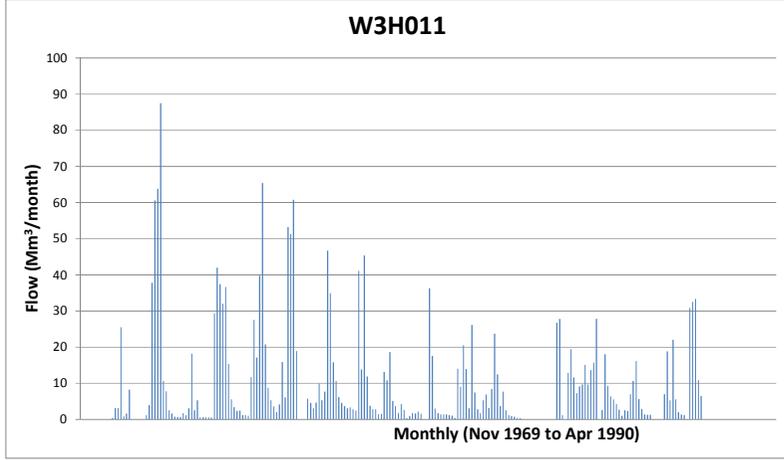
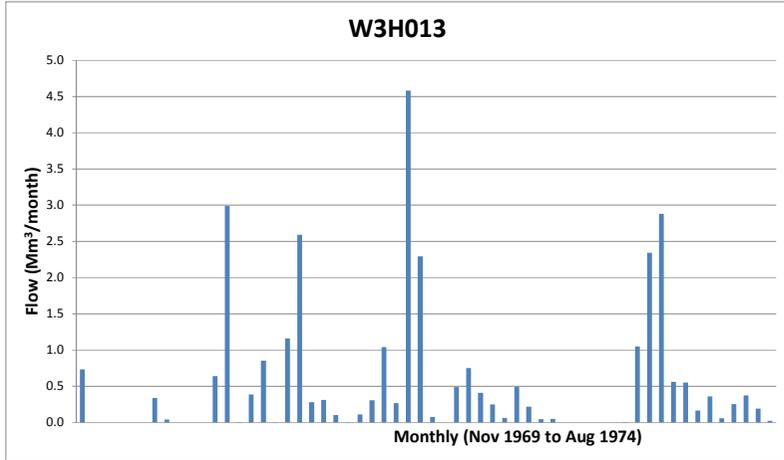


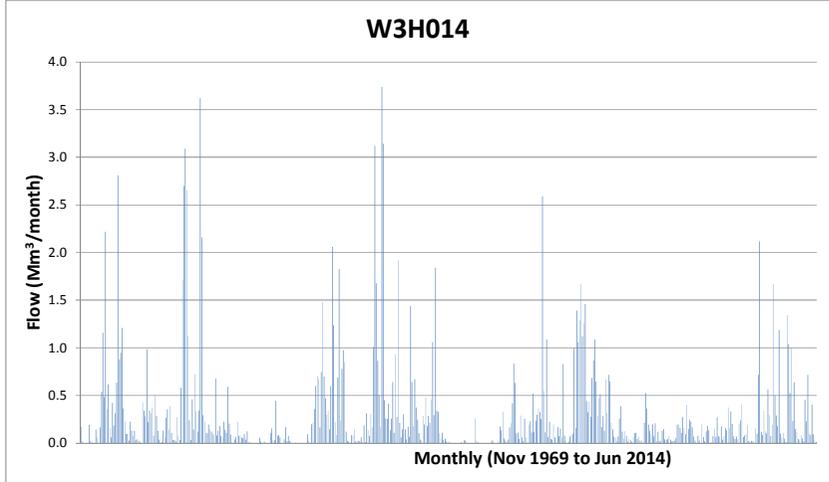
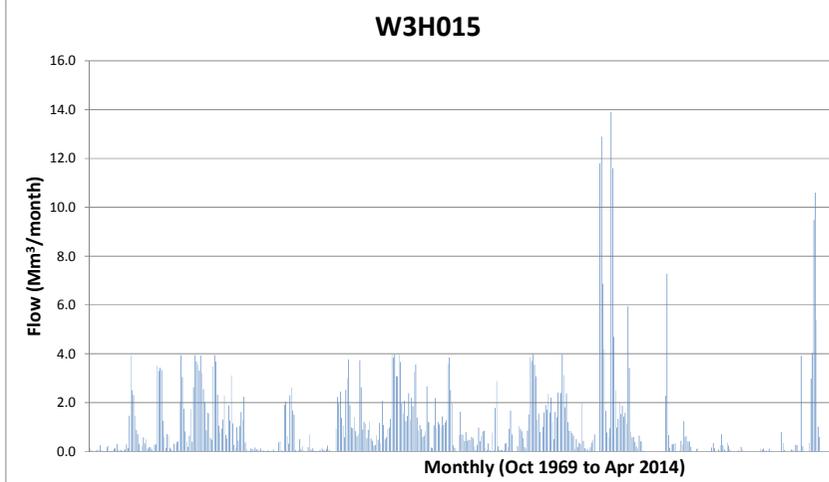
Figure A1-7: Mean Annual Precipitation Graph for the W45A Catchment.

Appendix B: Flow data from the DWA Gauges in the Study Area

Table B-1: Flow data from the DWA Gauges in the Study Area, (<http://www.dwaf.gov.za/Hydrology>)

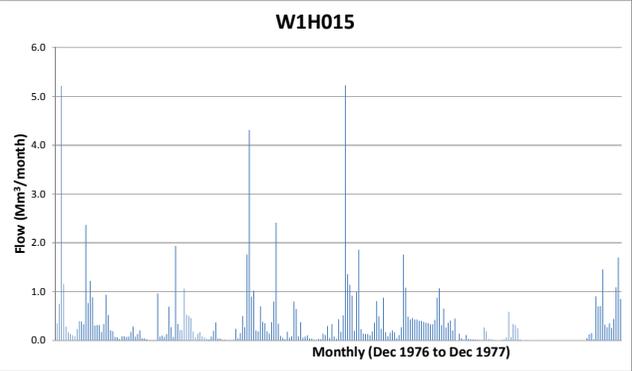
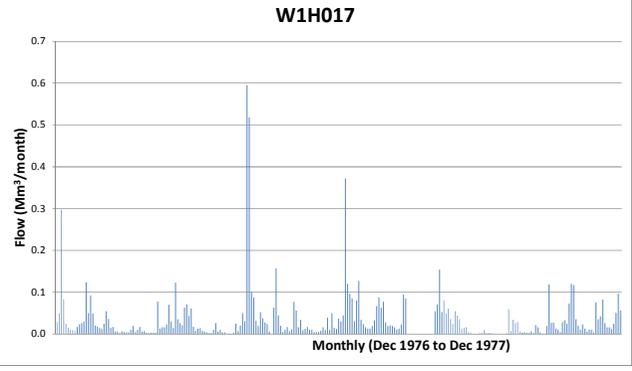
Quaternary Catchment ¹⁰	Flow station	Quality of data	Flow graph																
W32B	W3H011	<table border="1"> <thead> <tr> <th data-bbox="506 331 913 360"><i>Description</i></th> <th data-bbox="920 331 1070 360"><i>Value</i></th> </tr> </thead> <tbody> <tr> <td data-bbox="506 368 913 397">Start Date</td> <td data-bbox="920 368 1070 397">1969-11-01</td> </tr> <tr> <td data-bbox="506 405 913 434">End date</td> <td data-bbox="920 405 1070 434">1990-04-01</td> </tr> <tr> <td data-bbox="506 442 913 470">Good continuous data</td> <td data-bbox="920 442 1070 470">63.00%</td> </tr> <tr> <td data-bbox="506 478 913 507">Minimum Value</td> <td data-bbox="920 478 1070 507">2.00%</td> </tr> <tr> <td data-bbox="506 515 913 544">No info for stage/discharge</td> <td data-bbox="920 515 1070 544">8.10%</td> </tr> <tr> <td data-bbox="506 552 913 580">Rating missing</td> <td data-bbox="920 552 1070 580">0.40%</td> </tr> <tr> <td data-bbox="506 588 913 617">Permanent Gap</td> <td data-bbox="920 588 1070 617">26.40%</td> </tr> </tbody> </table>	<i>Description</i>	<i>Value</i>	Start Date	1969-11-01	End date	1990-04-01	Good continuous data	63.00%	Minimum Value	2.00%	No info for stage/discharge	8.10%	Rating missing	0.40%	Permanent Gap	26.40%	 <p style="text-align: center;">W3H011 Monthly (Nov 1969 to Apr 1990)</p>
<i>Description</i>	<i>Value</i>																		
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End date	1990-04-01																		
Good continuous data	63.00%																		
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No info for stage/discharge	8.10%																		
Rating missing	0.40%																		
Permanent Gap	26.40%																		
W32H	W3H013	<table border="1"> <thead> <tr> <th data-bbox="506 839 913 868"><i>Description</i></th> <th data-bbox="920 839 1070 868"><i>Value</i></th> </tr> </thead> <tbody> <tr> <td data-bbox="506 876 913 904">Start Date</td> <td data-bbox="920 876 1070 904">1969-11-01</td> </tr> <tr> <td data-bbox="506 912 913 941">End date</td> <td data-bbox="920 912 1070 941">1974-08-01</td> </tr> <tr> <td data-bbox="506 949 913 978">Good continuous data</td> <td data-bbox="920 949 1070 978">84.50%</td> </tr> <tr> <td data-bbox="506 986 913 1015">Above Rating</td> <td data-bbox="920 986 1070 1015">10.30%</td> </tr> <tr> <td data-bbox="506 1023 913 1051">Permanent Gap</td> <td data-bbox="920 1023 1070 1051">5.20%</td> </tr> </tbody> </table>	<i>Description</i>	<i>Value</i>	Start Date	1969-11-01	End date	1974-08-01	Good continuous data	84.50%	Above Rating	10.30%	Permanent Gap	5.20%	 <p style="text-align: center;">W3H013 Monthly (Nov 1969 to Aug 1974)</p>				
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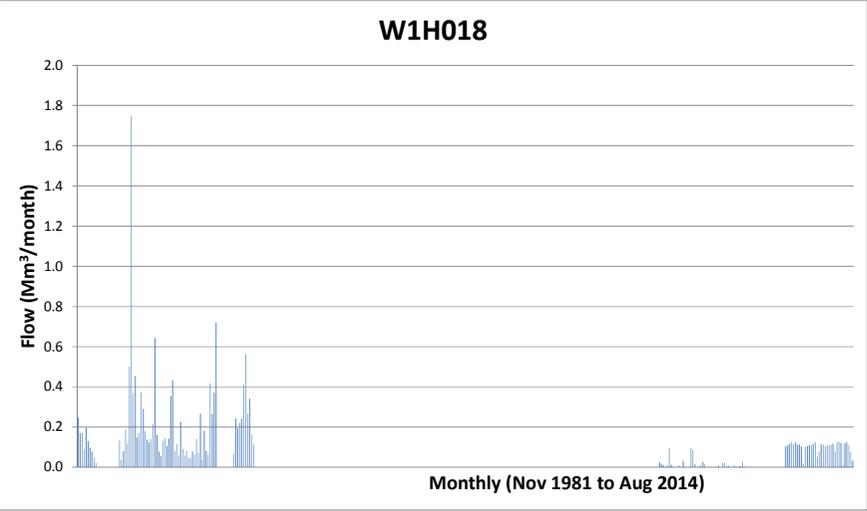
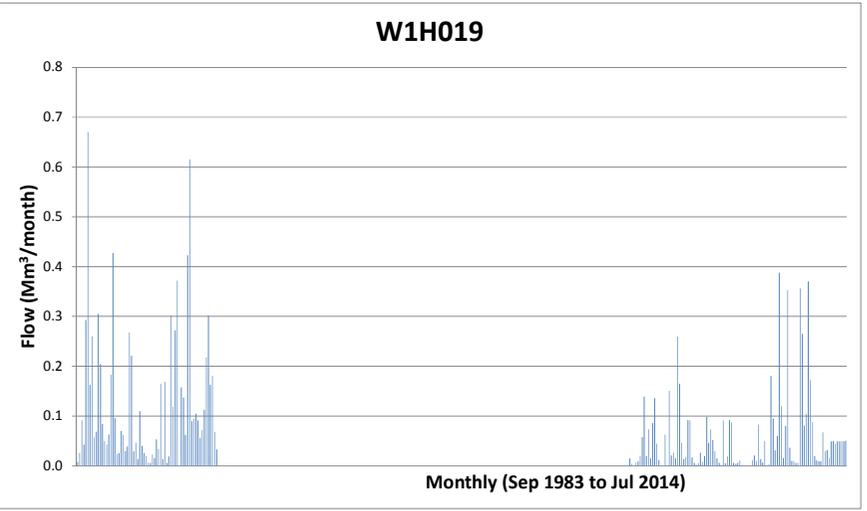
¹⁰ Where flow data is available.

Quaternary Catchment ¹⁰	Flow station	Quality if data	Flow graph																								
	W3H014	<table border="1"> <thead> <tr> <th data-bbox="506 264 913 295"><i>Description</i></th> <th data-bbox="913 264 1072 295"><i>Value</i></th> </tr> </thead> <tbody> <tr> <td data-bbox="506 295 913 325">Start Date</td> <td data-bbox="913 295 1072 325">1969-11-01</td> </tr> <tr> <td data-bbox="506 325 913 355">End date</td> <td data-bbox="913 325 1072 355">2014-06-01</td> </tr> <tr> <td data-bbox="506 355 913 386">Good continuous data</td> <td data-bbox="913 355 1072 386">65.50%</td> </tr> <tr> <td data-bbox="506 386 913 416">Good edited data</td> <td data-bbox="913 386 1072 416">17.50%</td> </tr> <tr> <td data-bbox="506 416 913 446">Unaudited</td> <td data-bbox="913 416 1072 446">0.40%</td> </tr> <tr> <td data-bbox="506 446 913 477">Good edited unaudited</td> <td data-bbox="913 446 1072 477">3.20%</td> </tr> <tr> <td data-bbox="506 477 913 507">Audited Gauge Plate Readings / dip level</td> <td data-bbox="913 477 1072 507">0.70%</td> </tr> <tr> <td data-bbox="506 507 913 537">Above Rating</td> <td data-bbox="913 507 1072 537">7.30%</td> </tr> <tr> <td data-bbox="506 537 913 568">Minimum Value</td> <td data-bbox="913 537 1072 568">0.20%</td> </tr> <tr> <td data-bbox="506 568 913 598">Permanent Gap</td> <td data-bbox="913 568 1072 598">5.20%</td> </tr> </tbody> </table>	<i>Description</i>	<i>Value</i>	Start Date	1969-11-01	End date	2014-06-01	Good continuous data	65.50%	Good edited data	17.50%	Unaudited	0.40%	Good edited unaudited	3.20%	Audited Gauge Plate Readings / dip level	0.70%	Above Rating	7.30%	Minimum Value	0.20%	Permanent Gap	5.20%	 <p style="text-align: center;">W3H014 Monthly (Nov 1969 to Jun 2014)</p>		
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	W3H015	<table border="1"> <thead> <tr> <th data-bbox="506 802 913 833"><i>Description</i></th> <th data-bbox="913 802 1072 833"><i>Value</i></th> </tr> </thead> <tbody> <tr> <td data-bbox="506 833 913 863">Start Date</td> <td data-bbox="913 833 1072 863">1969-10-01</td> </tr> <tr> <td data-bbox="506 863 913 893">End date</td> <td data-bbox="913 863 1072 893">2014-04-01</td> </tr> <tr> <td data-bbox="506 893 913 924">Good continuous data</td> <td data-bbox="913 893 1072 924">46.20%</td> </tr> <tr> <td data-bbox="506 924 913 954">Good edited data</td> <td data-bbox="913 924 1072 954">27.50%</td> </tr> <tr> <td data-bbox="506 954 913 984">Good edited unaudited</td> <td data-bbox="913 954 1072 984">2.60%</td> </tr> <tr> <td data-bbox="506 984 913 1015">Audited Gauge Plate Readings / dip level</td> <td data-bbox="913 984 1072 1015">1.30%</td> </tr> <tr> <td data-bbox="506 1015 913 1045">Above Rating</td> <td data-bbox="913 1015 1072 1045">17.00%</td> </tr> <tr> <td data-bbox="506 1045 913 1075">Audited Estimate</td> <td data-bbox="913 1045 1072 1075">0.90%</td> </tr> <tr> <td data-bbox="506 1075 913 1106">No info for stage/discharge</td> <td data-bbox="913 1075 1072 1106">0.60%</td> </tr> <tr> <td data-bbox="506 1106 913 1136">Permanent Gap</td> <td data-bbox="913 1106 1072 1136">3.70%</td> </tr> <tr> <td data-bbox="506 1136 913 1166">Data Missing</td> <td data-bbox="913 1136 1072 1166">0.20%</td> </tr> </tbody> </table>	<i>Description</i>	<i>Value</i>	Start Date	1969-10-01	End date	2014-04-01	Good continuous data	46.20%	Good edited data	27.50%	Good edited unaudited	2.60%	Audited Gauge Plate Readings / dip level	1.30%	Above Rating	17.00%	Audited Estimate	0.90%	No info for stage/discharge	0.60%	Permanent Gap	3.70%	Data Missing	0.20%	 <p style="text-align: center;">W3H015 Monthly (Oct 1969 to Apr 2014)</p>
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Quaternary Catchment ¹⁰	Flow station	Quality of data	Flow graph																				
W12J	W1H011	<table border="1"> <tr> <td>Start Date</td> <td>1968-05-01</td> </tr> <tr> <td>End date</td> <td>2006-07-01</td> </tr> <tr> <td>Good continuous data</td> <td>64.50%</td> </tr> <tr> <td>Good edited data</td> <td>6.10%</td> </tr> <tr> <td>Above Rating</td> <td>1.10%</td> </tr> <tr> <td>No info for stage/discharge</td> <td>0.90%</td> </tr> <tr> <td>Permanent Gap</td> <td>24.60%</td> </tr> <tr> <td>Not Defined</td> <td>1.70%</td> </tr> <tr> <td>Data Unreliable</td> <td>0.90%</td> </tr> <tr> <td>Data Missing</td> <td>0.20%</td> </tr> </table>	Start Date	1968-05-01	End date	2006-07-01	Good continuous data	64.50%	Good edited data	6.10%	Above Rating	1.10%	No info for stage/discharge	0.90%	Permanent Gap	24.60%	Not Defined	1.70%	Data Unreliable	0.90%	Data Missing	0.20%	
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W12F	W1H012	<table border="1"> <thead> <tr> <th>Description</th> <th>Value</th> </tr> </thead> <tbody> <tr> <td>Start Date</td> <td>1977-08-01</td> </tr> <tr> <td>End date</td> <td>2000-01-01</td> </tr> <tr> <td>Good continuous data</td> <td>48.90%</td> </tr> <tr> <td>Good edited data</td> <td>10.70%</td> </tr> <tr> <td>Above Rating</td> <td>2.20%</td> </tr> <tr> <td>Audited Estimate</td> <td>2.20%</td> </tr> <tr> <td>Permanent Gap</td> <td>35.90%</td> </tr> </tbody> </table>	Description	Value	Start Date	1977-08-01	End date	2000-01-01	Good continuous data	48.90%	Good edited data	10.70%	Above Rating	2.20%	Audited Estimate	2.20%	Permanent Gap	35.90%					
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